INVESTIGATION INTO CONTINUOUS SPRAY AND METERED SPRAY USING COMPRESSED GAS PROPELLANT

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DECLARATION

“**I Milton Mateus João Miguel**, declare that this thesis is submitted in fulfilment of the requirements for the degree of MRes, in The University of Salford. This dissertation is a presentation of my original research work. Wherever contributions of others are involved, every effort is made to indicate this clearly, with due reference to the literature, and acknowledgement of collaborative research and discussions.”

The work was done under the guidance of Professor G. G. Nasr and Dr Amir Nourian, at the University of Salford, Manchester.

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DEDICATION

This work is dedicated to my father Miguel Pessoa and my mother Suzarina Pessoa without whose love, support and encouragement it would not have possible.

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ABSTRACT

In general all the domestic aerosol products use hydrocarbon propellants (i.e. butane and propane) in which a high flash vaporisation provides a good atomisation. However, according to the 2015 United Nations Climate Change Conference agreed in Paris, these propellants have the adverse climatic effects due to the level of VOC's (Volatile Organic Compound) which can lead to greenhouse gases. The agreement has given an impetus to industry to significantly reduce these harmful gases by 2020. Therefore, an alternative energy is required to replace the corresponding hydrocarbon compositions by utilising safer propellant such as compressed gas (i.e. Nitrogen or air). Although the energy of the compressed gas is about 70 times lower than the hydrocarbon propellants. The new valving arrangement which was used in this study, is however introducing the propellant into the valve stem to create 'bubbly flow' thus increasing the turbulence prior to the atomiser insert of the actuator. The domestic aerosol products are generally based on either spraying continuously (i.e. airfreshners, body spray, hairspray, insecticide, polish and disinfectant) or on spraying on metered liquid dosage.

This investigation has focused on two different aerosol products: (i) *Continuous* spraying aerosol with matching valve_actuator using compressed gas propellant (ii) *Metered* aerosol product for airfreshners, using a specially design compressed gas valve with 'L' shape actuator and MBU (Mechanical Breakup Unit) inserts which are normally used as wall-mounted devise.

The new valve design for *continuous spray* is performing similar to the current commercial products with hydrocarbon propellants in terms of spraying discharge rate and drop size through the packlife. Nevertheless, due to the nature of the compressed gas which contains significant level of moistures, as the main propellant, the applied sprays could inevitably be wetter with an increase dryness time which are not acceptable by the consumers. The challenge of this study therefore was to identify a robust solution to reduce the discharge rate to about 0.30 g/s to 0.50 g/s and average particle size, $D_{v50,}$ 30 µm to 40 µm through the can life. The results found here showed that the low discharge rates with conforming droplet sizes are achievable and thus providing substantive reduction in the wetness of approximately 50% compared to the high discharge rates (i.e. 1.4 g/s – 1.1 g/s).

Although the novel *metered* valve design which was used in this investigation, has been developed successfully to employ compressed gas as a propellant. However, the design needed to be diligently modified since the valve had presented an acceptable double actuation (or liquid dosage) after each pulse. Moreover, the valve appeared to cause some liquid leakages which were deposited around the stem and around the mounting cup after each actuation. This study presented a modified design of the *metered valve* stem that prevents the liquid droplet leakage which could have otherwise led to dysfunctionality of the valve and the mounting wall devise. This was carried out by redesigning and relocating the stem liquid holes on the upper chamber of the stem together with the reduction of the stroke of the stem. These modifications were thus prevented the double actuation of liquid dosage on each pulse using the metered valve_'L' shape actuator_MUB insert. The results presented the constant discharge rate of 50 µL to 120 µL through the packlife of the can with average drop size, $D_{v50,}$ of 60 µm – 70 µm using the relevant wall mounting devises.

CHAPTER 1

INTRODUCTION

1.1. Overview

In the field of consumer aerosol, compressed gases can be used as replacement of conventional propellants (such as butane); such gases includes air and nitrogen (so called compressed gas aerosols) which also offer a number of technical challenges that have limited their application in the market, despite their environmental advantages. There is insufficient atomisation power, leading to the spray having a large droplet size and inferior spray pattern. This becomes noticeable to the consumer, as a ‘wet’ spray, rather than the fine mist consumers expect. Significant drop off in spray ‘power’ as the can is depleted due to the reduced volume of liquid in the can to be sprayed causing a corresponding decrease in pressure. Consumers notice a further reduction in spray performance as well as not having full recovery of the product.

1.2. Contribution to Knowledge

This investigation contributes to (i) reducing the wetness by lowering the discharge rate (typically from1.4 g/s to less than 1.1 g/s) using different product mixtures and EcoValve with compressed gas propellant (i.e. Nitrogen) for the *continuous spray* of the domestic aerosol products, (ii) the prevention of the deposition of the droplets around the corresponding stem of the *metering valving* arrangement upon actuation as well as obtaining lower liquid dosage, from average of 120 µL to 50 µL.

1.3. Aims and Objectives

This investigation has focused on two different aerosol products: (i) *Continuous spraying* aerosol with matching valve actuator using compressed gas propellant (ii) *Metered aerosol* product for airfreshners, using a specially design compressed gas valve with ‘L’ shape actuator and MBU (Mechanical Breakup Unit) inserts which are normally used as wall-mounted devise.

The *first* aim of this investigation is to reduce the discharge rates of the new valve technology, for continuous spray, using inert gases (i.e. Nitrogen) that are comparable wetness with the current domestic aerosol products which are normally pressurised by hydrocarbon propellant (i.e. butane and propane). The aerosol products considered in this study are mainly body sprays in which the amount of products that depleted from the pressurised cans give a minimum wetness when sprayed onto the body, this is mainly due to the nature of the moisture contents that are normally presented in the compressed gas propellants.

The main challenge of this study was therefore to reduce the discharge rate of the spray that can be comparable to that of the current products with hydrocarbon propellants whilst maintaining the same spray performance. The following objectives were thus achieved throughout this investigation:

- The discharge rate of the spray was reduced from 1.4 g/s to less than 1.1 g/s throughout the life of the can thus producing lower wetness. This was carried out by modifying the stem mixing channel and designing new insert geometry of the actuator in obtaining lower discharge rate with constant particle sizes from 60 µm to 70 µm through pack life of the can.
- In addition, the valves were tested using deionised water and ethanol mixture, simulating the cosmetic aerosol products, as well as using several leading brand formulations for comparative purposes.

The *second* aim of this study is to preclude the droplets deposition around the stem of the new aerosol metered valve with compressed gas. This outcome of this study is applicable to the inhalers, nasal sprays as well as automatic (wall-mounted) dispensers for air-fresheners, insecticides and disinfectants. The objectives of this investigation were thus:

- To modify the current new metered valve designs in avoiding a second pulsation when the valve is open (no metered liquid dosage). This was conducted through experimentation in which the liquid holes on stem were moved lower down the stem. Thus enabling the holes to be sealed off, by the resultant inner gasket, when the valve is in fully open position.
- To modify the housing of the valve to obtain lower dosage rates. This was carried out by increasing the length of the spigot inside the housing which led in reduction of the liquid dosage from average of 120 µL to 50 µL.

1.4. Structure of the Thesis

This thesis consists of the following chapters:

- *Chapter 2:* The General Background on Spray and Atomisation
- *Chapter 3:* The General Background on Aerosol Valves (Continuous Spray and Metered Valve)
- *Chapter 4:* Design, Experimental Apparatus and Method of Data Processing
- *Chapter 5:* Results and Discussions
- *Chapter 6:* Conclusion and Future Work

CHAPTER 2

THE GENERAL BACKGROUND ON SPRAY ATOMISATION

2.1. Overview

The atomisation process of a liquid into smaller droplets in the form of a fine spray plays an important role in various industrial applications. Sprays and atomisation techniques have attracted the attention of many researchers and have been the subject of a wide range of theoretical and experimental studies during the past decade. Many studies concerning different aspects of sprays and atomisation have been performed and major advancements in spray analysis and spray characterisation have been made. This Chapter thus, presents a general background of sprays and atomisation processes. Spray properties and different representative mean drop sizes' diameters are defined. The spray properties, factors influencing atomisation and atomisers classification will be discussed.

2.2. The Fundamental of Spray and Atomisation

There are many ways in which spray can be produced and the basic method associated with atomization is the hydraulics of the flow inside the atomizer; this monitors the turbulence properties of the liquid steam that is being made [1]. Atomization is the disturbance of surface tension in the liquid phase caused by an external or internal force. In the system geometry the liquid viscosity and surface tension will act against it, and the aerodynamic forces cause disruption by acting on the liquid surface [2]. If the magnitude of the force that is disrupted is greater than the surface tension force, droplets will break-up and this is atomisation [4].

Spray nozzle requirements are dependent of the application as different applications require different criteria [1]. The basic functions of nozzle are to disperse droplets in a specific pattern, to control the liquid being released, to control the generation of the hydraulic momentum or impact and the atomisation of liquid into droplets [5]. Energy is important when trying to break up solutions or liquids and energy is created by pressure from a pump. In a pump pressure is converted into velocity by causing the liquid to pass through a restricted passage inside the nozzle [5]. The remaining energy is used to make liquid into droplets and cause them to disperse into specific spray patterns [1].

2.2.1. The Useful Properties of Sprays

For specific designs spray is characterised according to its pattern, penetration, droplet size distribution, particle mean diameters and any factor which affects the droplets [5]. These can be changed by carefully designing the atomiser insert and the nozzle valve arrangement [2]. This allow the achievement the expected performance of the aerosol product [12].

2.2.2. Factor Affecting the Spray Wetness

Spray wetness study is carried out, to make sure that the spray product is dry and it can be conveniently used by the general public [11]. While doing so it is important to make sure that the right particle size is established [8]. A big problem that can be found on sprays, is when they become runny and inconvenient. This is why this study is concentrating on the flow rate and particle size as well as measure of size distribution [7]. At the current time there has not been any publications or research on characterization of spray wetness of domestic aerosol valve; this project is new. Therefore it is not possible to find any inconsistencies in results or gaps of information at this moment in time [7].

Spray Patternation

Each spray type has different types of nozzles and these can be classified as hallow cone spray, full cone spray and flat fan spray. These patterns depend on internal geometry and the flow inside the atomiser [2]. There are different sprays for specific applications, and the use of different nozzles will depend on, the viscosity of the liquid, the ratio between the orifice length and orifice diameter, the operating pressure, forces of aerodynamics, spray pattern flow rate, the spray angle and others. All of this is particle important for household products like hair spray and body spray [2].

(a) Hollow Cone Spray (b) Full Cone Spray (c) Flat Fan Spray

Figure 2.1: Spray Patternations

Discharge Rate (mass flow rate or volume flow rate)

The actual flow rate of the nozzle is affected by specific gravity, viscosity and pressure; the nozzle capacity is dependent of the water tolerance being between $\pm$ 5% on the rate of flow [2]. The volume of liquid flowing through a nozzle depends primarily on the difference in fluid pressure upstream of its orifice and the pressure into which the nozzle discharges (normally that of the atmosphere) [1]. If we want to measure the rate at which water is flowing along a pipe. A very simple way of doing this is to catch all the water coming out of the pipe in a bucket over a fixed time period. Measuring the weight of the water in the bucket and dividing this by the time taken to collect this water gives a rate of accumulation of mass [5]. This is known as the mass flow rate.

$$\text{mass flow rate} = \frac{\text{Weight Difference for a Period of Time (gr)}}{\text{Time (sec)}}$$

Spray Cone Angle

Spray angles are measured close to the nozzle orifice and with a tolerance of $\pm$ 5° on tested spray angles [4]. The droplets are affected by gas friction and gravity as the distance of spray increases, this decreases the spray angle [2].

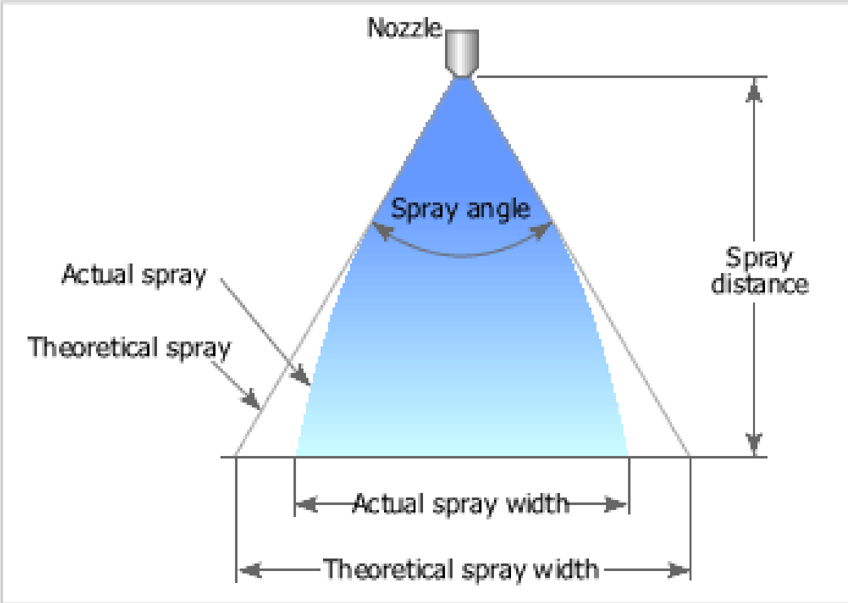


Figure 2.2: Spray angle

Product

When using a liquid other than water there are several things that may change that is able to affect the nozzle type that should be used, the optimum material of manufacture and operating pressure are viscosity, surface tension, specific gravity and temperature [2].

Mean drop size

Mean diameter is used to make the calculation of evaporation rate easier and to allow the comparison of atomisation qualities of different sprays [2].

$$\mathrm{SMD} = \frac{\sum \mathrm{D}^3}{\sum \mathrm{D}^2}$$

D is droplet size and mass median diameter; this represents the drop diameter above or below 50% of the mass drop [1].

The key element in choosing an atomiser for a specific application is drop size. Drop size distribution is an important parameter of the atomisation process in addition to droplet mean diameter [8]. Certain shapes may be better for certain operations (for example, narrow, wide, a few large drops or a few small drops) [2]. It is known that, to improve the quality of atomisation, it is important to reduce droplet size. According to Lefebvre (1989), drop size distribution may be obtained by plotting a histogram of drop size, each ordinate representing the number of drops whose diameter ranges between (D- D)/2 and (D+ D)/2, as shown in Figure 5.7, in which D = 5 µm.

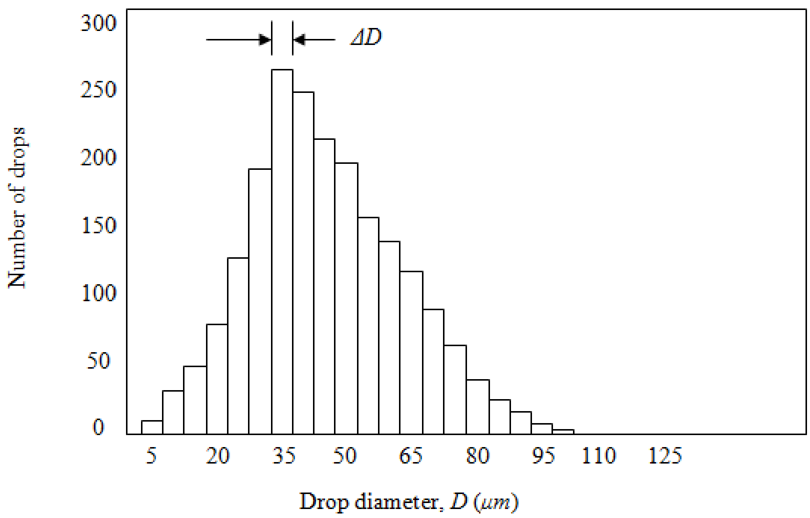


Figure 2.3: Typical drop size distribution

If the spray volume corresponding to a range of drop size between (D-ΔD)/2 and (D+-ΔD)/2, is plotted as a function of drop size, as shown in Figure below, the resulting distribution is skewed to the right due to the larger drops' weighing effect [11].

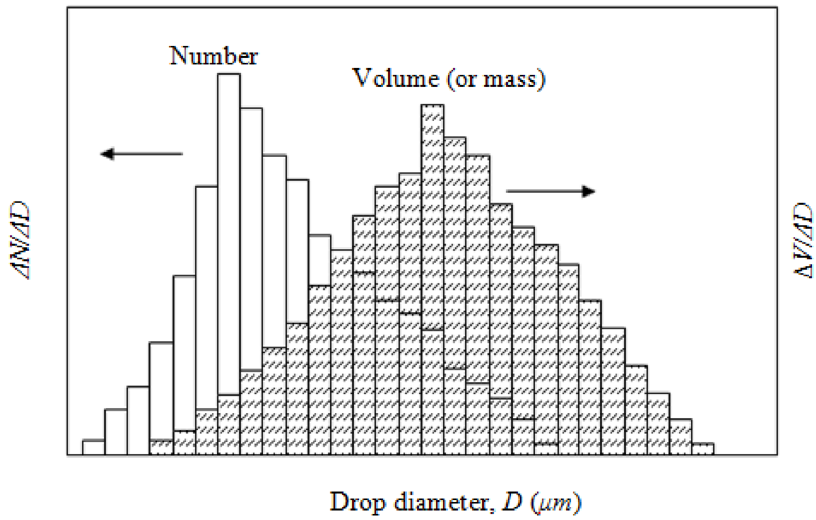


Figure 2.4: Drop size histograms based on number and volume (Lefebvre, 1989)

CHAPTER 3

THE GENERAL BACKGROUND ON AEROSOL VALVES (CONTINUOUS SPRAY AND METERED VALVE)

3.1. Overview

Until the 1980s most aerosol cans were used ChloroFluoroCarbons (CFCs) as a propellant, however CFCs it is harmful to the ozone layer [9]. In 1982 seventy nations signed the Montreal Protocol, to change CFCs regulation [7]. Currently almost all aerosol cans use Liquefied Petroleum Gas (LPG, i.e. Butane), and according to the UK government the total estimated VOC emission = 800,000 tonnes/year (refineries and coating). UK alone could increase the VOC by 40% via domestic aerosol market share using LPG [10].

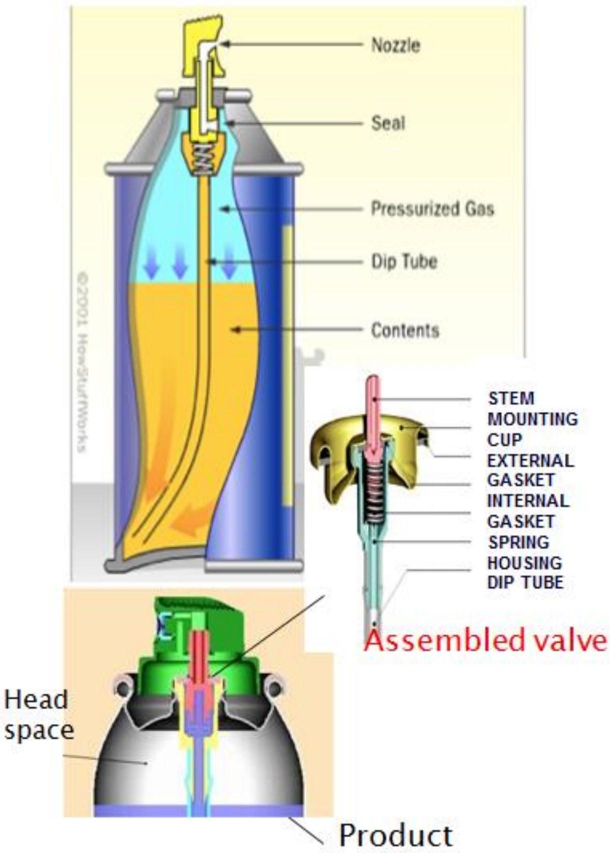


Figure 3.1: Conventional aerosol can

3.2. Components of Aerosol Cans

Typically, aerosol valves are composed of seven components [2,12]. Following are the common components;

- Spring loaded valve is depressed by actuator cap
- Actuator fits on valve stem & contains channel leading to exit orifice
- “Insert” contains the exit orifice which is often a pressure swirl atomizer
- Vapour phase tap (VPT) is optional: allows propellant vapour into the liquid flow to the valve

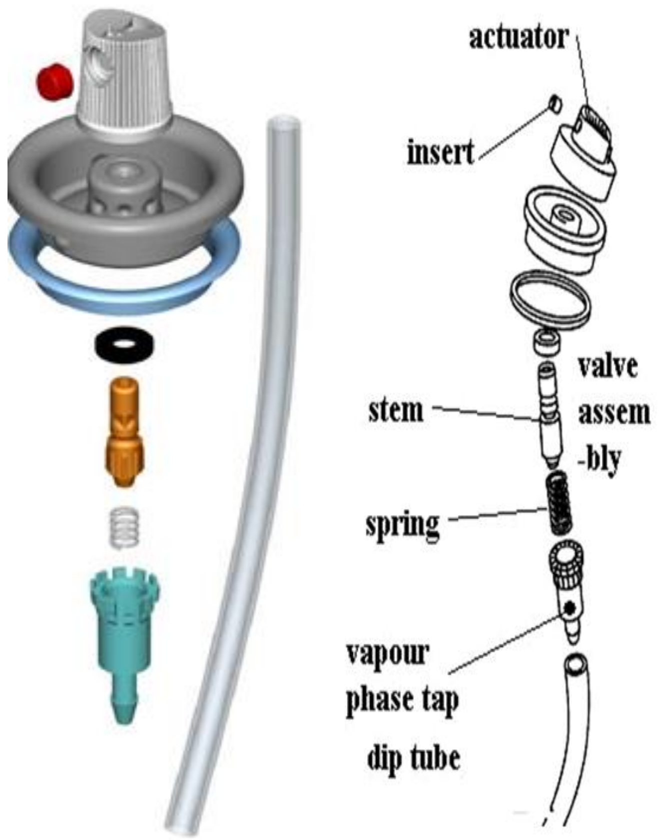


Figure 3.2: Aerosol valve components

3.3 Bubbly flow

Bubbly flow comes about when a small proportion of compressed gas within the can is injected directly into the passing flow of product within the valve assembly [2]. Effervescence is the process of various actively introducing gas bubbles into a liquid flow, immediately upstream of the exit orifice, thereby forming a two-phase flow. In addition, effervescent atomising prediction for modelling drop size was recently made by on high viscosity material such as gelatinised starch suspension.

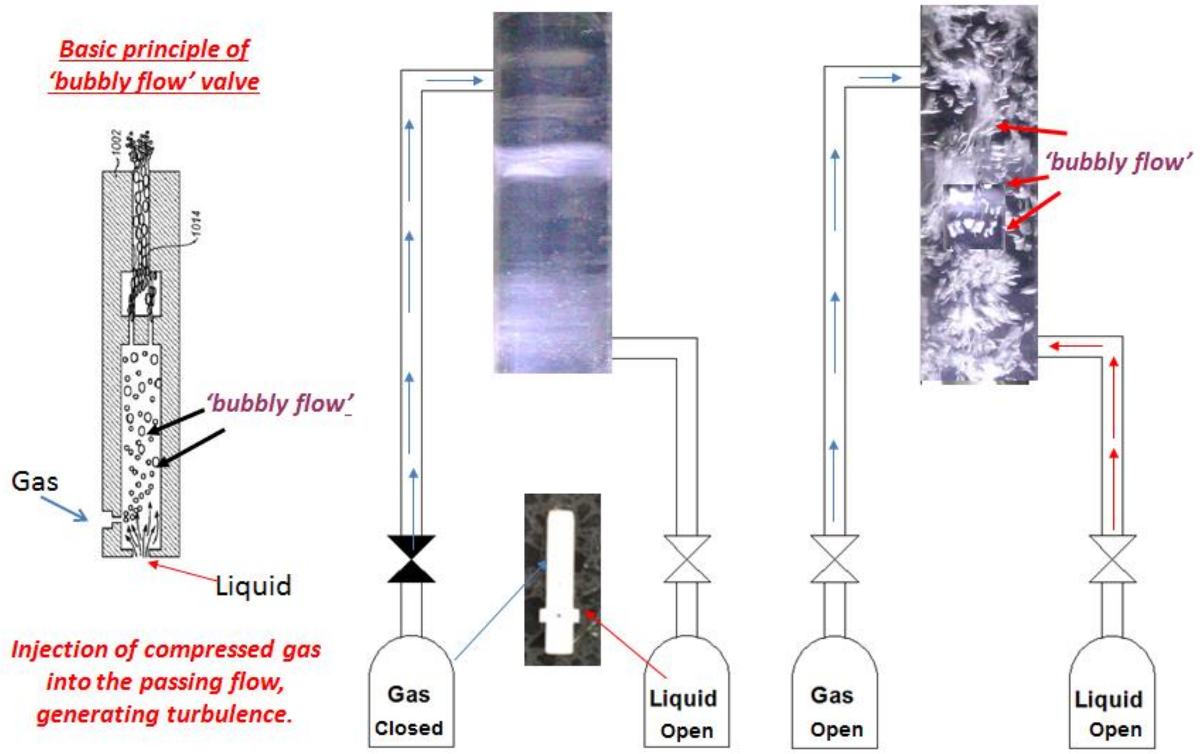


Figure 3.3: Bubbly Flow schematic

3.4 Current design of SSG Valve

The SSG valve are the simplest conventional domestic aerosol valve for *continuous spray* using inert gases as propellant and it has three parts, which are stem, housing and gasket. The current design is called as 'super single gasket (SSG)' and the valve designs were developed to give the required 'bubbly flow' generation [2]. Figure 3.4 shows the SSG valve assembly which has only one gasket, and when the stem is moved downward to produce spray, the liquid hole should pass the ridge whilst the gas hole is still above the ridge. It is noted that the ridge does not need to be a perfect tight seal but rather is a sliding fit [2]. This is because the gas pressure above and the liquid pressure below the ridge are nearly equal.

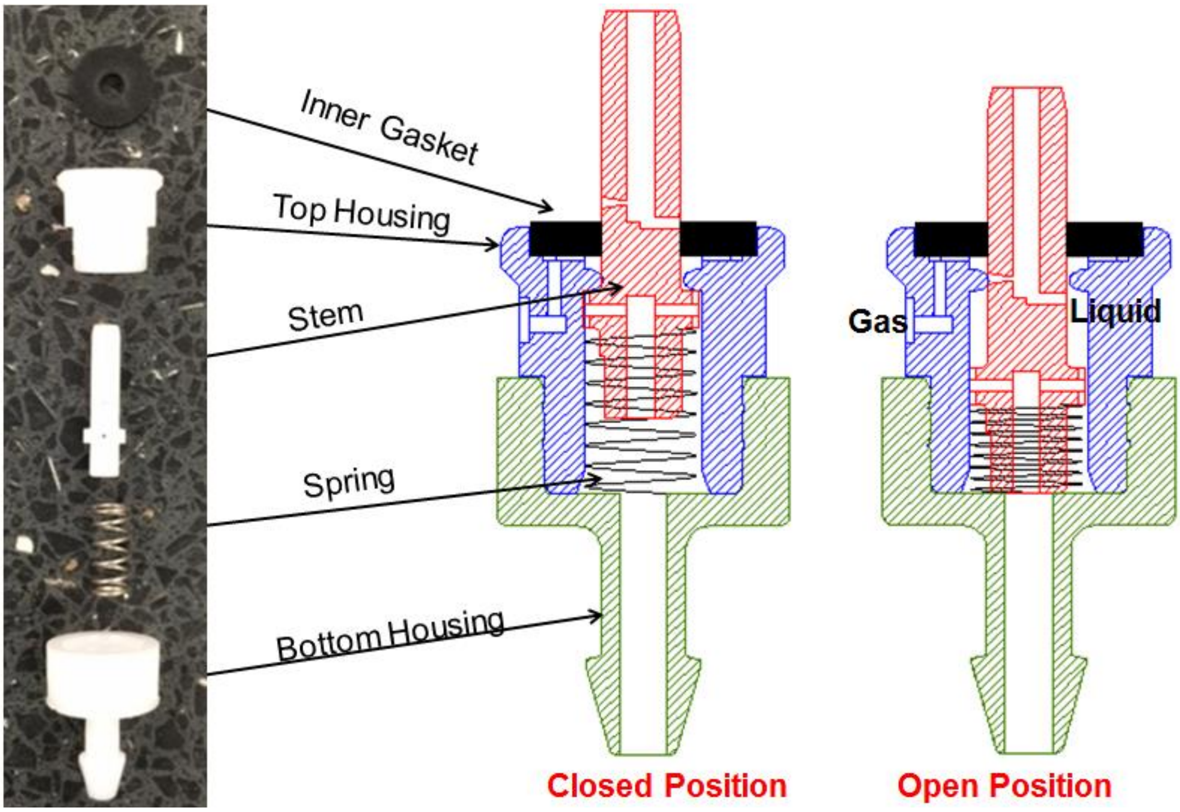


Figure 3.4: Current SSG Design

3.5 Metered Valve for Compressed Air

The *Metered Valve* design is divided into just two components (the stem and housing) by injection moulding and where the only additional component, compared with current liquefied gas propellant metered valves, is a 'piston element'. As described in patents covering the valve, a key and novel step in the design evolution is the positioning of the metering chamber inside the stem. This is shown in Figure 3.5, which shows axial sections of the valve at two times in its operating sequence. This positioning of the metering chamber greatly simplifies the design and requires only two components to be made by injection moulding [2].

Figure 3.5 (left) illustrates an axial section of the metered valve, where the central valve member (valve stem) is in its normal rest position. The valve stem is at this full movement, vertically upwards, and the spherical piston is at its fully downwards position, the metering chamber is fully charged with liquid. Figure 3.5 (right) shows the valve where the valve stem has been fully depressed downwards and the metering chamber has been fully evacuated of liquid, as can be seen with the spherical piston in the fully upward position.

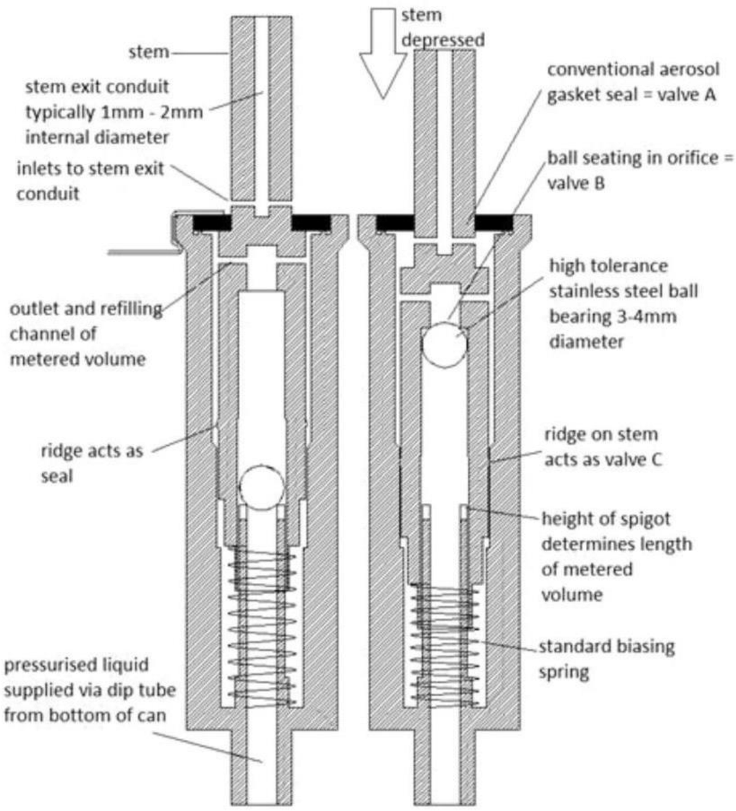


Figure 3.5: The new compressed gas metered valve: (left) at rest and primed and (right) stem depressed and full metered volume sprayed

During development of the device, interesting and useful features of the use of the spherical piston balls became clear. It had an initial concern that it would be necessary for the ball to be quite a tight fit inside the chamber in order to transmit force to the metered liquid without leakage and this would cause friction problems and also problems with returning the ball to the bottom of the chamber, probably by a spring system. This would cause complexity and also a loss of pressure at the insert and thus poor atomization.

3.6 Installation of the new metering valve in commercial aerosol products

The device is designed to operate in the vertical, or near vertical, orientation, but this is not a restriction for most applications. Figure 3.6 show the valve mounted in the top of a standard aluminium or steel container (can), where it would have the top part crimped into a metal cup of the aerosol can in the conventional manner: the can, dip tube, sealing gasket, cup and the dimensions of the upper ‘turret’ of the valve are of standard sizes in common usage in the aerosol can, valve and actuator industry. The upper part of the valve stem can also be one of the standard dimensions in current usage, so that commercially available actuator caps and spraying nozzles (inserts) can be fitted on to it. An automatic electrical actuator depression system would normally be used, as shown in Figure 3.7, as part of a wall or shelf mounted aerosol for air-fresheners or insecticides [2].

A standard compressed gas format aerosol can be used with aqueous or ethanol-based liquid product in the container and air or nitrogen gas (propellant) pressurizing the container [1,2]. Air can be used if there are no potential problems due to flammability of product or bacterial growth. There are regulations and guidelines regarding the design, pressures, filling and safety of such systems, determined in Europe by the European Commission [9].

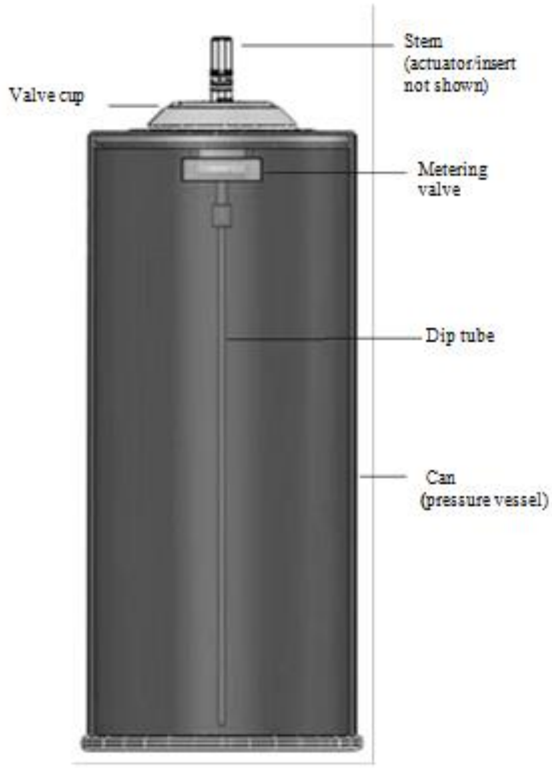


Figure 3.6: Valve assembled within a can

When using liquefied gas propellant, the atomization process is dominated by the flash vaporization of the propellant inside the insert and this is essentially a two-fluid (high velocity gas–lower velocity liquid) atomization process, known to be excellent for fine atomization [1,3]. Therefore, a simple orifice can often be used for the insert. However, for compressed gas propellant, where a single phase liquid flows through the insert without a change in phase, the design of the atomizer insert is critically important and the most suitable device is a miniature swirl atomizer [1]. This causes liquid break up by forming a thin conical liquid sheet for the emerging jet that then breaks up via waves and perforations into a well atomized spray [2]. In the consumer aerosol industry, these miniature swirl atomizer inserts are mass produced by injection moulding of polymer and known as mechanical break up units (MBUs).

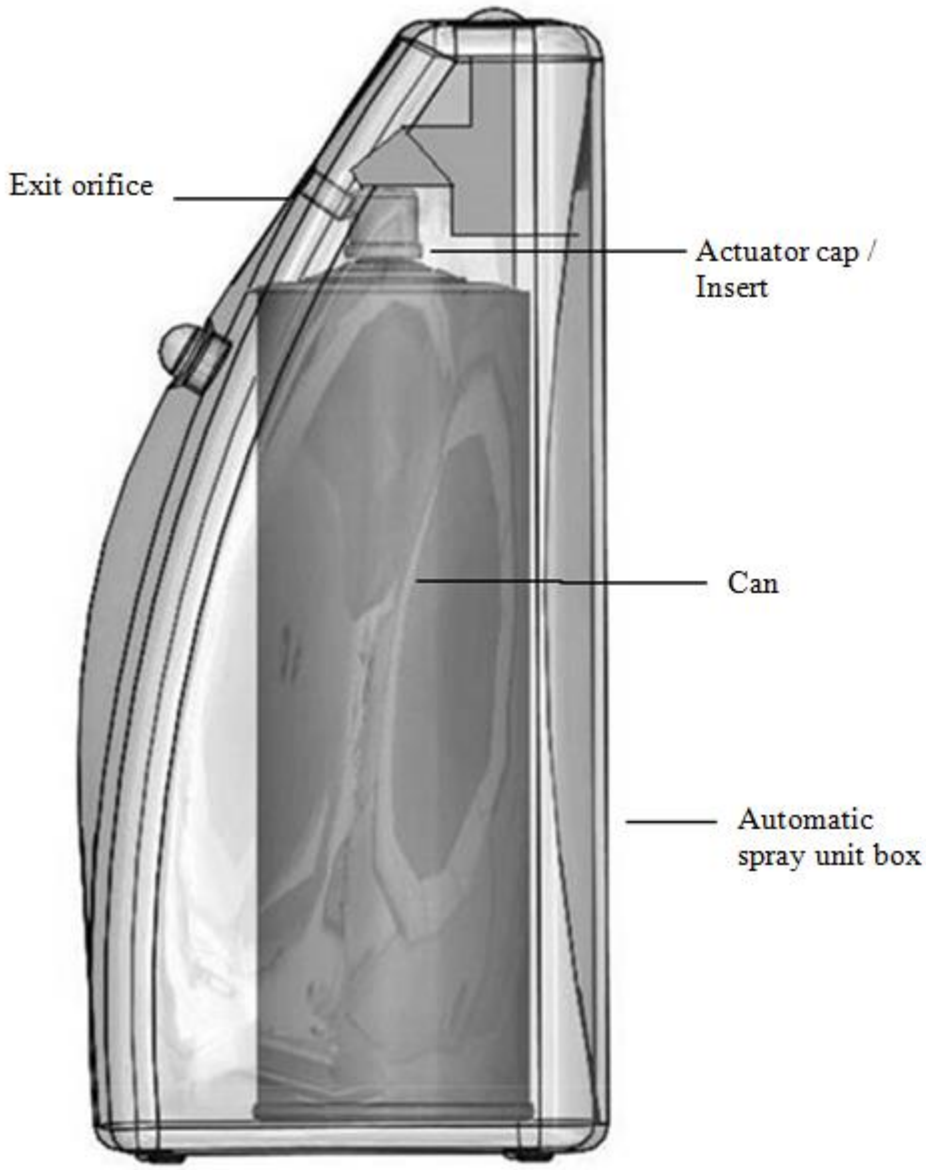


Figure 3.7: Aerosol can mounted in automatic spray unit

CHAPTER 4

DESIGN, EXPERIMENTAL APPARATUS AND METHODOLOGY OF DATA PROCESSING

4.1. Overview

This Chapter presents first the designs which were used through this study, followed by the experimental apparatus utilised to obtain the data subsequent to the experimental procedures and data acquisition for both Continuous Spray and Metered Valve.

4.2. Design

4.2.1. Continues Spray

The continuous valves used in this study are the modification of the current SSG stem design to reduce the discharge rate thus decrease the level of wetness using insert gases (i.e. Nitrogen) as a propellant to be compatible with the current LPG products like body spray and hair spray which are available in the market.

As explained in Table below, these modifications have been made to reduce or increase the stem mixing channel as well as increasing the gas hole dimeter but the liquid holes remains same in all combinations (0.50 mm). This section will provide the various valve stem design combinations of the aerosol valve using inert gases as a propellant.

Table 4.1: Different Stem Combinations

Stem No.	Stem Code	Stem Mixing Chamber (mm)	Stem Gas Hole (mm)
0 (Current Design)	#11000205	1.1	0.2
1	#11000305	1.1	0.3
2	#11000405	1.1	0.4
3	#11140205	1.4	0.2
4	#11140305	1.4	0.3
5	#11140405	1.4	0.4
6	#11050205	1.1 to 0.5	0.2
7	#11050305	1.1 to 0.5	0.3
8	#11050405	1.1 to 0.5	0.4

4.2.1.1. Current Stem Design

Figure 4.1 shows the current valve stem design of the SSG valve which has mixing channel with 1.1 mm diameter, gas hole of 0.20 mm and liquid hole of 0.50 mm.

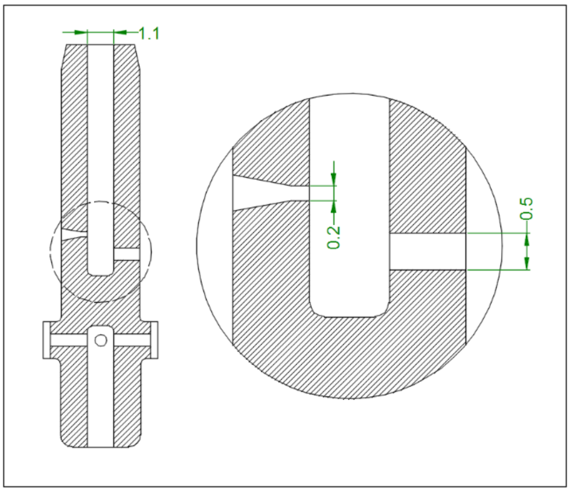
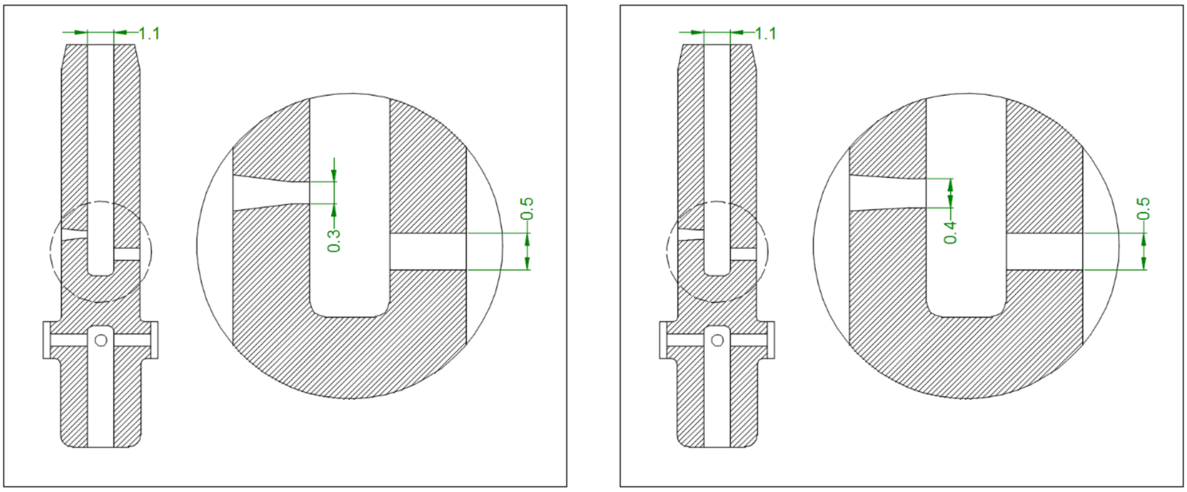


Figure 4.1: Current Design of the SSG Aerosol Valve

Next Section is describing the all modifications which have been made in this study to achieve the lower and constant discharge rate through the packlife.

4.2.1.2. Modifications on Stem Valve Design – Stem #1 and Stem #2

Figure 4.2 shows the schematic design of the stem #1 (code: 11000305) and stem #2 (code: 11000405). The similarity of these designs and the current stem design (Stem #0) are the 1.1 mm mixing chamber through with the same liquid hole diameter of 0.50 mm, however, the gas hole has been increased in both designs (see Figure 4.2).



(a) (b)

Figure 4.2: Schematic Design of (a) Stem #1 (Code: 11000305) and (b) Stem #2 (Code: 11000405)

4.2.1.3. Modifications on Stem Valve Design – Stem #3, Stem #4 and Stem #5

Figure 4.3 shows the new set of stem design for the valve in which the stem channel has been increased to 1.4 mm all through with the same liquid hole size of 0.5 mm and different gas hole diameter from 0.2 mm to 0.4 mm.

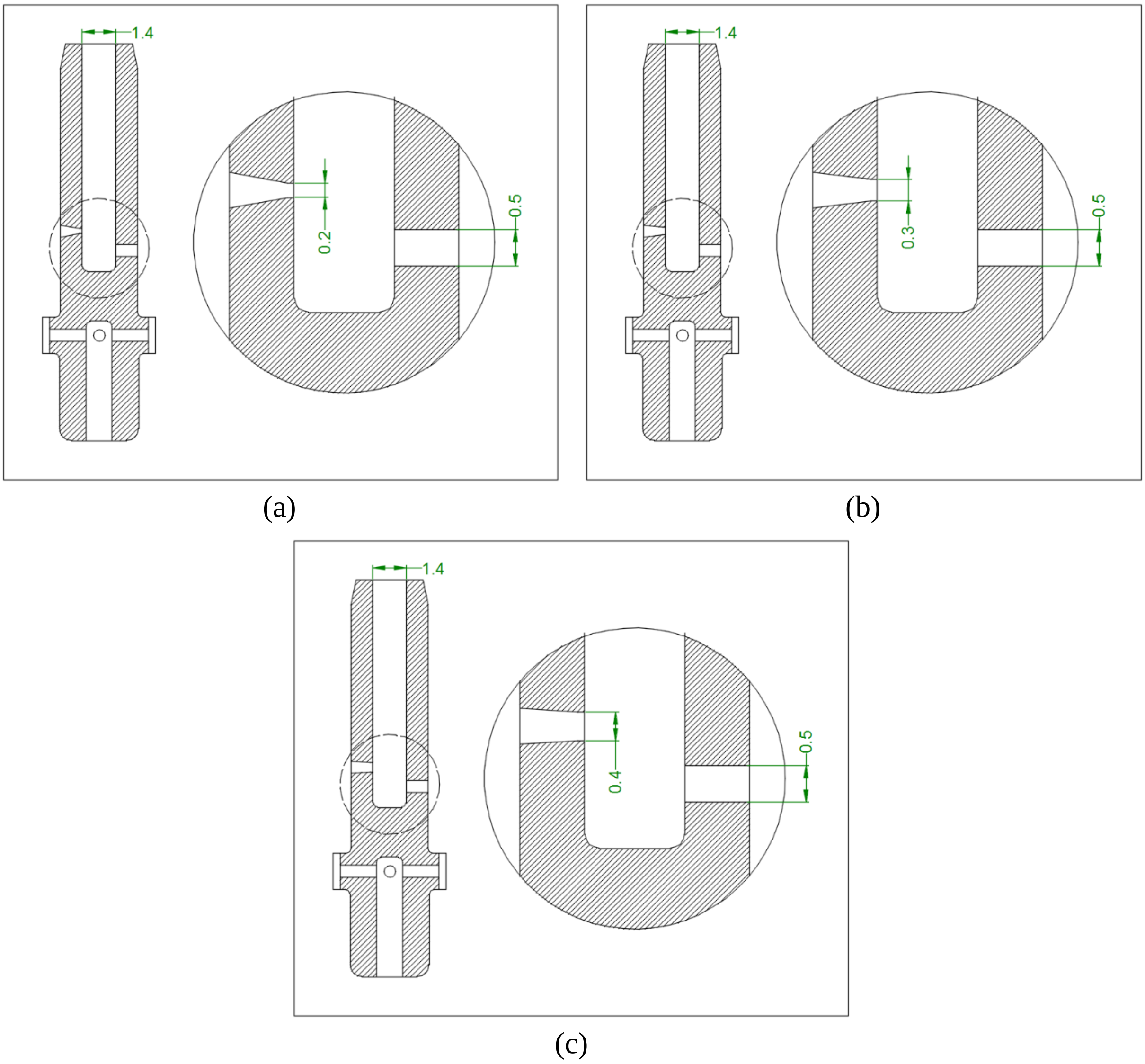
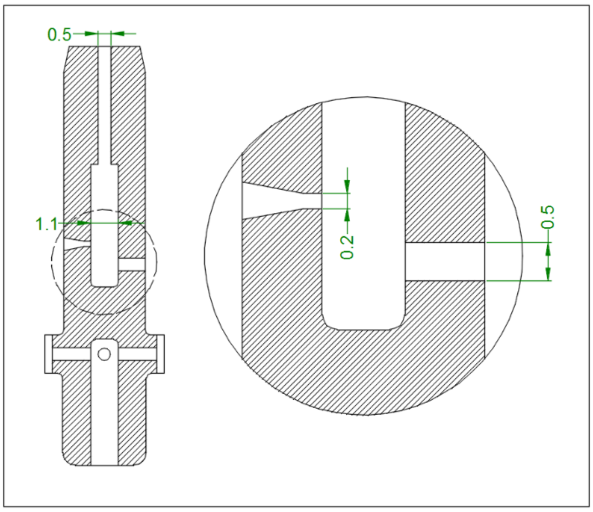


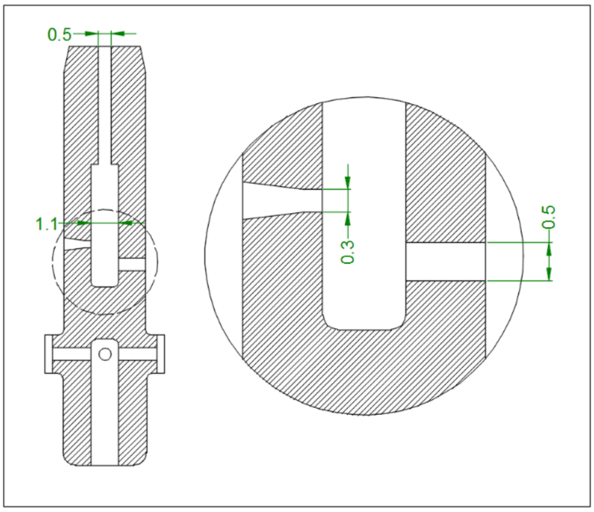
Figure 4.3: Schematic Design of (a) Stem #3 (Code: 14000205), (b) Stem #4 (Code: 14000305) and (c) Stem #5 (Code: 14000405)

4.2.1.4. Modifications on Stem Valve Design – Stem #6, Stem #7 and Stem #8

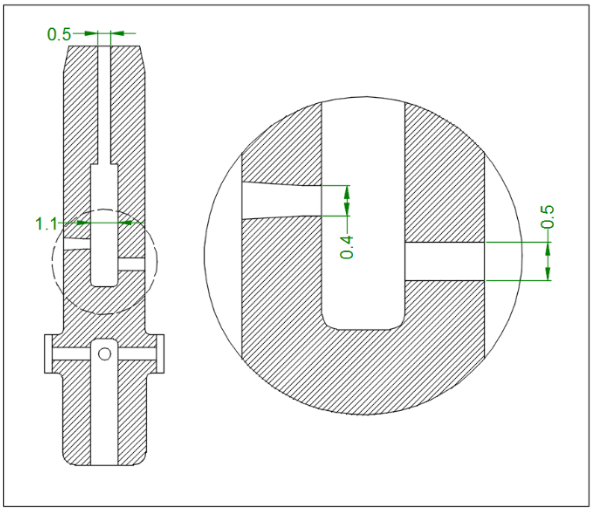
Figure 4.4 show a proposed new version of the valve stem design, with a new internal geometry, in which the stem mixing channel has 0.5 mm from the top to about half length of the channel and then increased to 1.1 mm for the rest of the channel. These stem designs have the same liquid hole of 0.5 mm but the gas holes are from 0.2 mm to 0.4 mm.



(a)



(b)



(c)

Figure 4.4: Schematic Design of (a) Stem #6 (Code: 11050205), (b) Stem #7 (Code: 11050305) and (c) Stem #8 (Code: 11050405)

In order to achieve this combinations and reduce the mixing chamber diameter, a brass pipe with 1 mm OD and 0.50 mm ID has been placed inside the mixing chamber (see Figure 4.5)

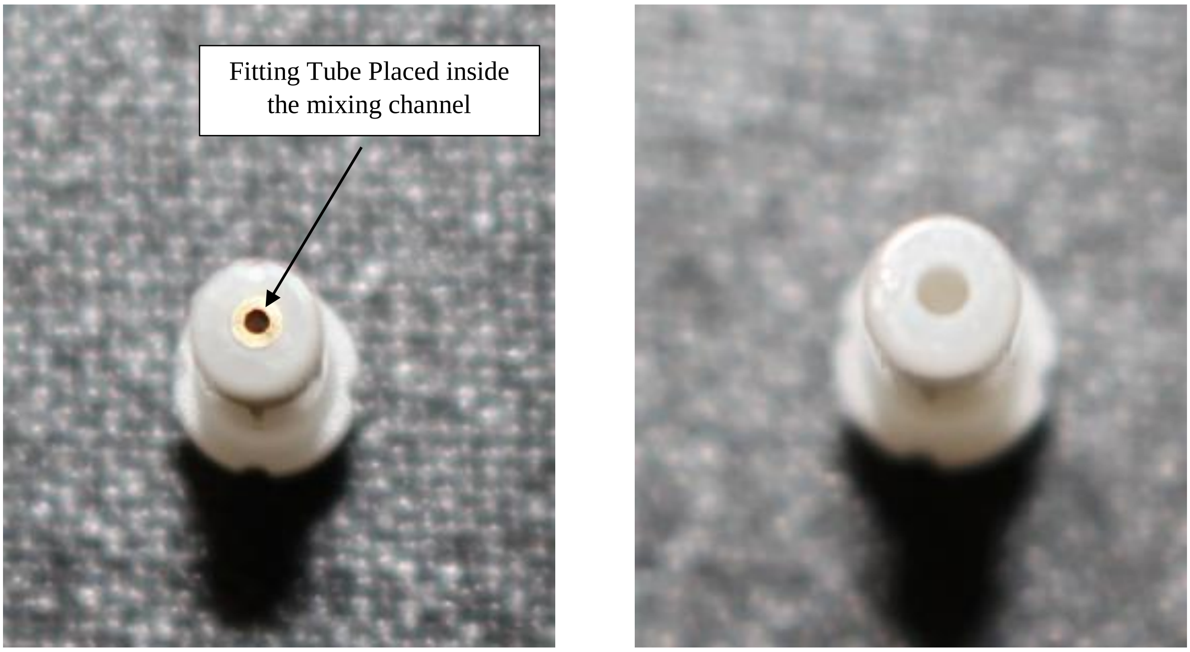


Figure 4.5: Top view of the Stem (a) with the Fitting tube and (b) without the Fitting Tube

4.2.2. Metered Valve

This section provides the details of the novel metered aerosol valve design in which the valve is spraying the certain amount of dosage per each burst. The valve can be used as a wall mounted airfreshener and also the inhalers. This section is also describing the issues of the current metered valve and also the new modification designs which have been made to eliminate these issues.

4.2.2.1. First Proposed Design of the Metered Valve

Figure 4.6 shows the schematic design of the first proposed design metered valve. As it shown below, the liquid is filling the dosage chamber above the ball when the valve is closed position. When the valve is in half position, the ridge on stem is blocking the liquid passage thus no liquid is coming continuously. Furthermore, when the valve is fully down, the top liquid holes on stem are open to the atmosphere thus the ball is moving up and spray the certain amount of liquid which seats on the chamber.

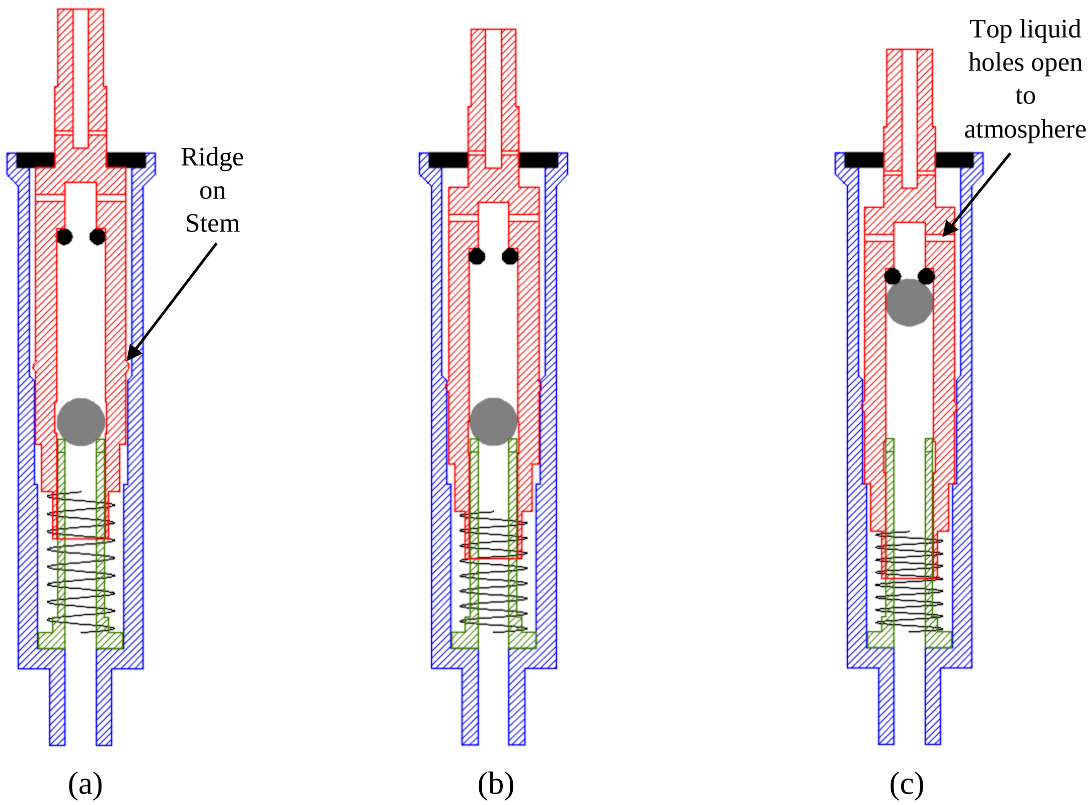


Figure 4.6: Schematic Design of the First Proposed Design of Metered Valve (a) Closed Position, (b) Half Position and (c) Open Position

4.2.2.2. Modification on Metered Valve Stem – Eliminate Residual Liquid

Although the valve performed well with water and provided constant discharge rate and particle size, but after some actuations as it shown in Figure 4.7, it appears that some small droplets to be build-up and sit on the cup pedestal around the stem when the valve is at up position.

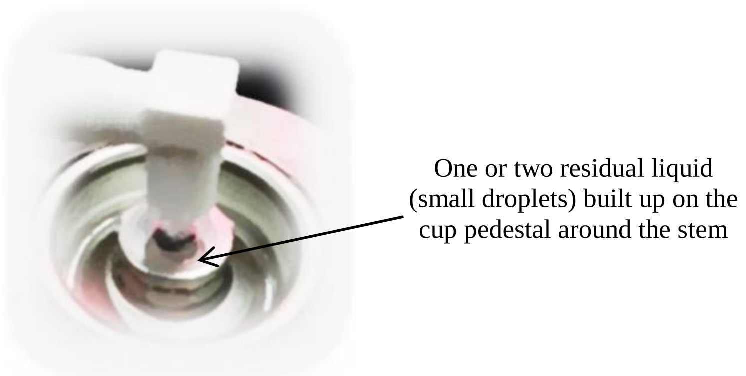


Figure 4.7: Residual Liquids Built Up on the Cup Pedestal

In order to eliminate the residual of the droplets on the pedestal, the top liquid holes on stem have been moved down to a position that when stem is in up position, those holes must be sealed by the inner gasket (see Figure 4.8).

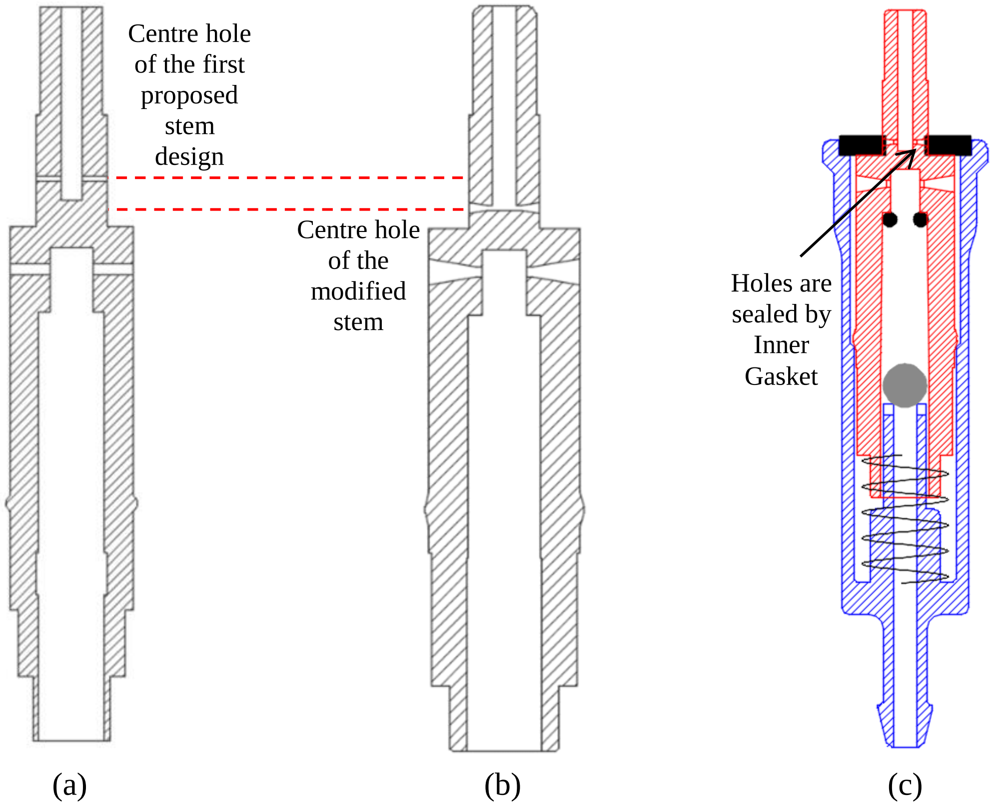
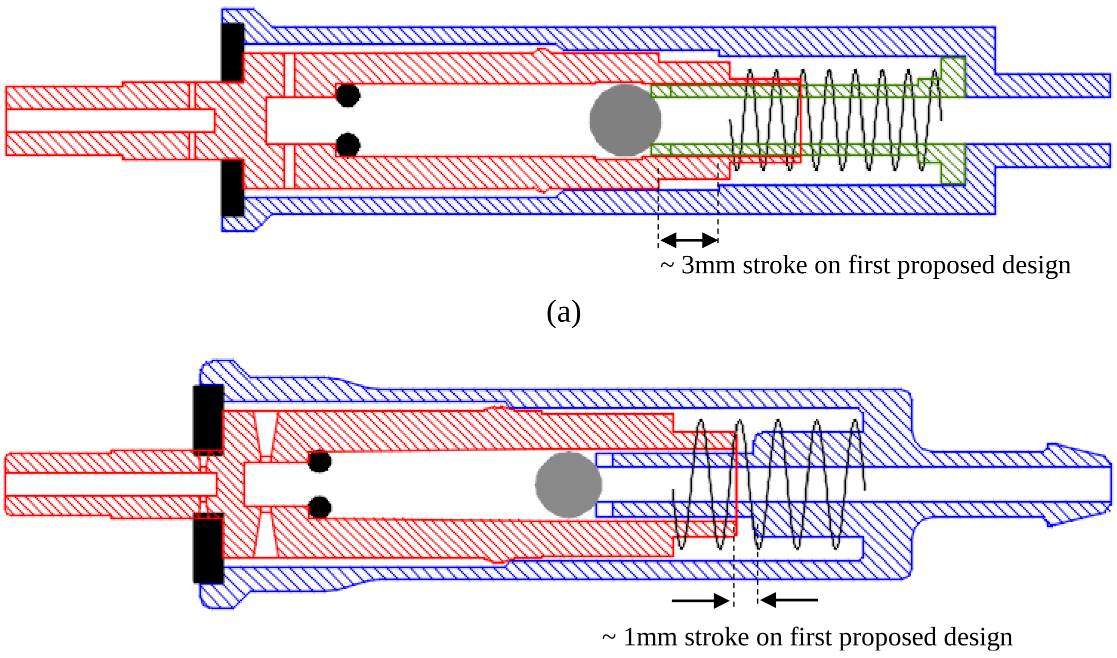


Figure 4.8: Schematic Design of the (a) First Porposed Metered Valve Stem, (b) The Modified Stem with Moving the Liquid Holes Down and (c) The assemble view in Closed Position

4.2.2.3. Modification on Metered Valve Housing – Stop Double Actuation

Although the first modification on metered valve stopped having the residual liquid on pedestal, however the valve demonstrated a double actuation which means the valve is actuating a small liquid upon closure of the valve (called here double actuation). In order to stop this non-acceptable issue, the new modification has been made onto the housing to have shorter stroke of the valve (from about 3 mm stroke reduced to 1 mm) thus the opening of the valve relies on bending of the inner gasket when stem is pushed down through each actuation (see Figure 4.9)



(b)

Figure 4.9: Schematic Design of the (a) First Proposed Metered Valve Assembly with about 3mm Stroke and (b) The Modified Housing to Reduce the Stoke to about 1mm

4.2.2.4. Modification on Metered Valve Housing – Reduce the Dosage

The application of the metered valve is wide within the aerosol industry, therefore the amount of the liquid on each burst is different depends on the application and it is within the range of 300 µL to 50 µL. In this novel metered valve design, the amount of liquid controls by the length of the spigot inside the housing. In order to achieve at least two different dosage, this study presents two different lengths as shown in Figure 4.10.

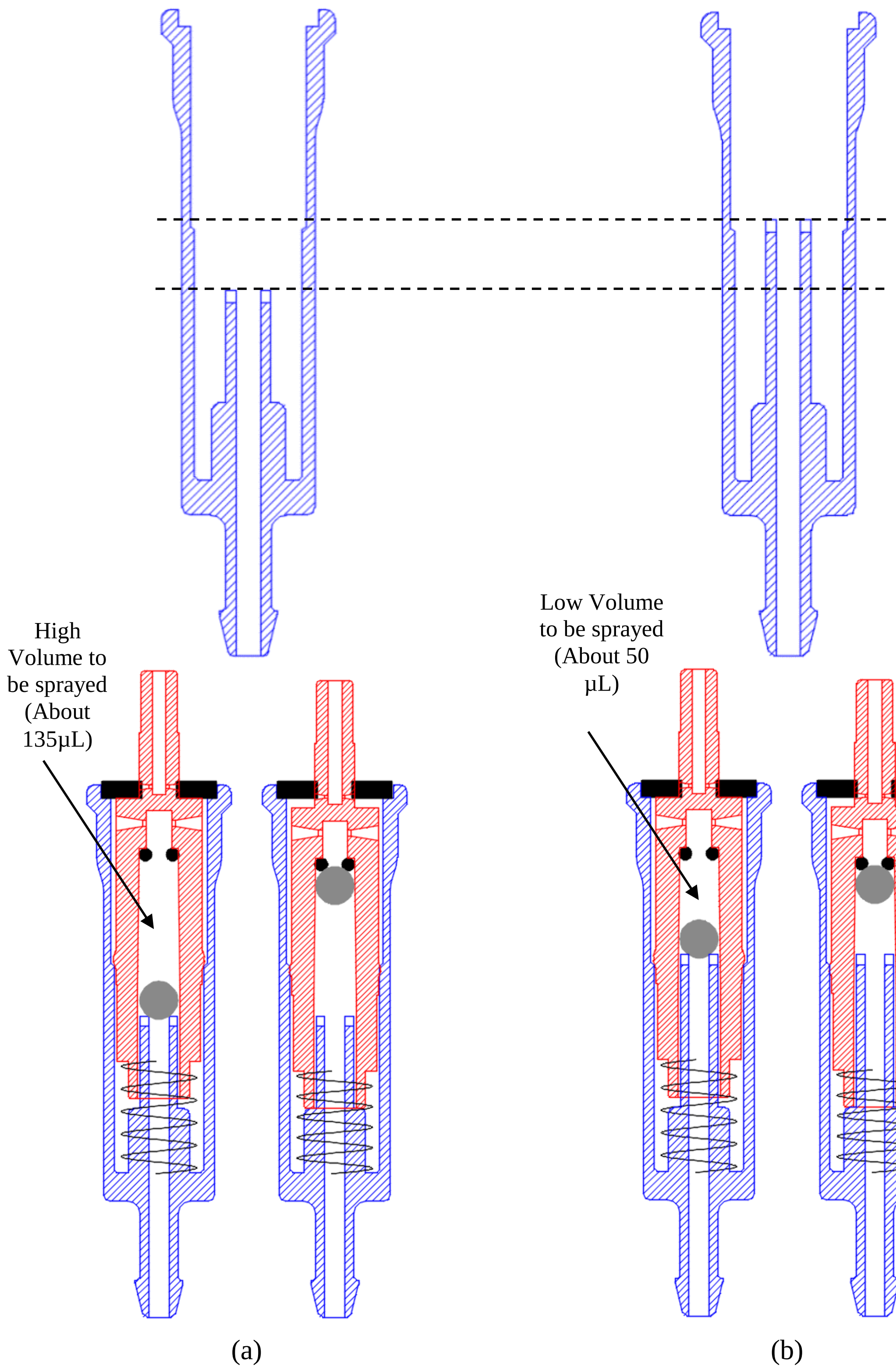


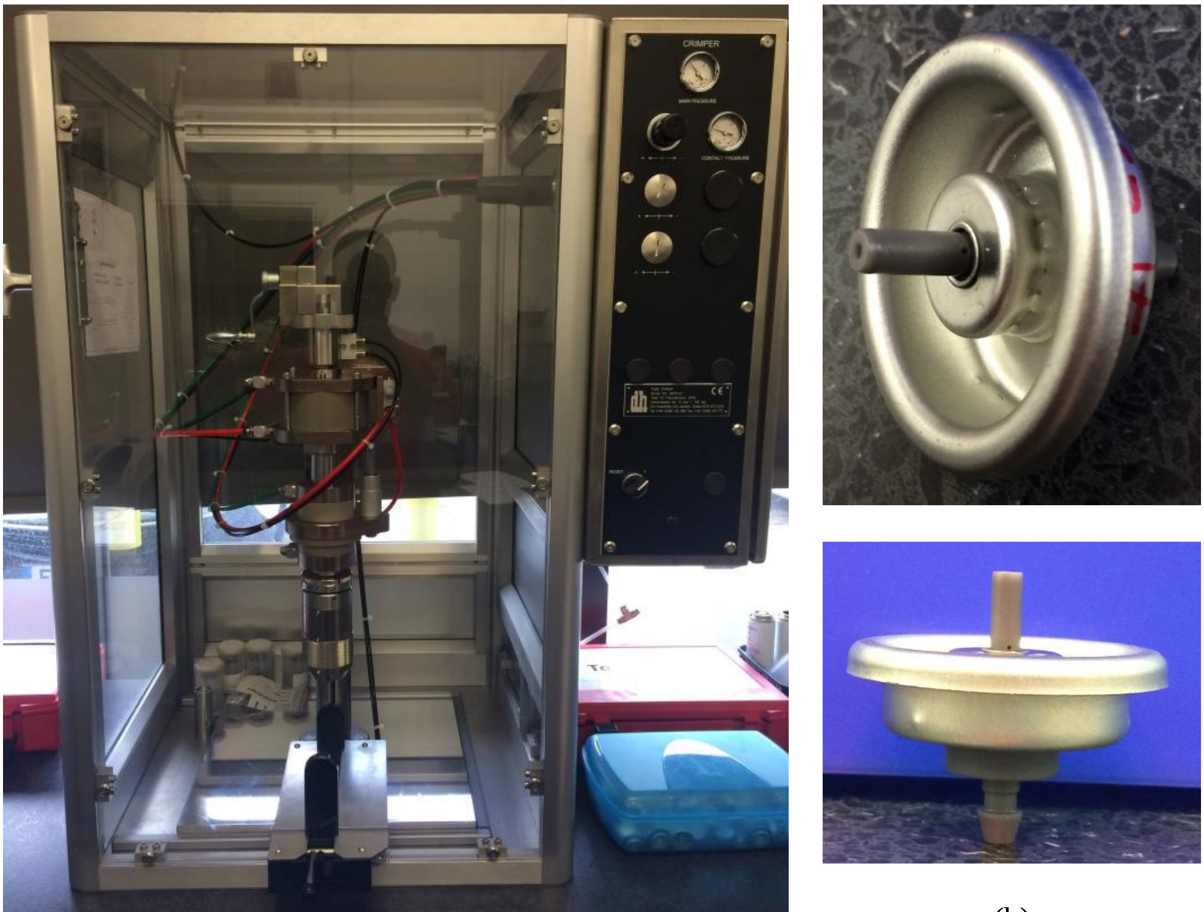
Figure 4.10: Schematic Design of (a) Housing produces on average 130 µL (High Dosage) on each burst and (b) Housing produces on average 50 µL (Low Dosage) on each burst

4.3. Experimental Apparatus

The following section describes the apparatus and instrumentation for both ***Continuous Spray*** and ***Metered Valve***. This includes: Crimping Machine, Glass Tube, Filling Method, Electronic Weight Scale, Pressure Gauge, Laser Diffraction Machine and Clinching Machine.

4.3.1. Crimping Machine

Figure 5.11 illustrates the crimping machine used in this investigation supplied by Pamasol (DHI-UK) in which all the assembled valve components attach onto the mounting cup.



(a) (b)

Figure 4.11: (a) The Crimping Machine Supplied by Pamasol (DHI-UK) and (b) The Image of the Valve Assembled onto the Mounting Cup

4.3.2. Glass Tube

A glass can with a capacity of 100 ml volume was used to model a conventional can with pressure of 10 bar. Figure 4.12 shows that a substance can be pressurised through the valve stem when is placed inside the can.

Figure 4.12: The Glass Tube

4.3.3. Filling Method

One commonly used aerosol filling method is known as the impact gassing; in this method the can is filled with a product and the valve used is crimped to the can and the propellant is injected into the can. In this particular investigation this method was used to fill the tinplate can. Figure 4.13, illustrates how cans were filled in this research; as it shows how the glass can is filled with the appropriate propellant pressure, and the pressure is checked with the pressure gauge.

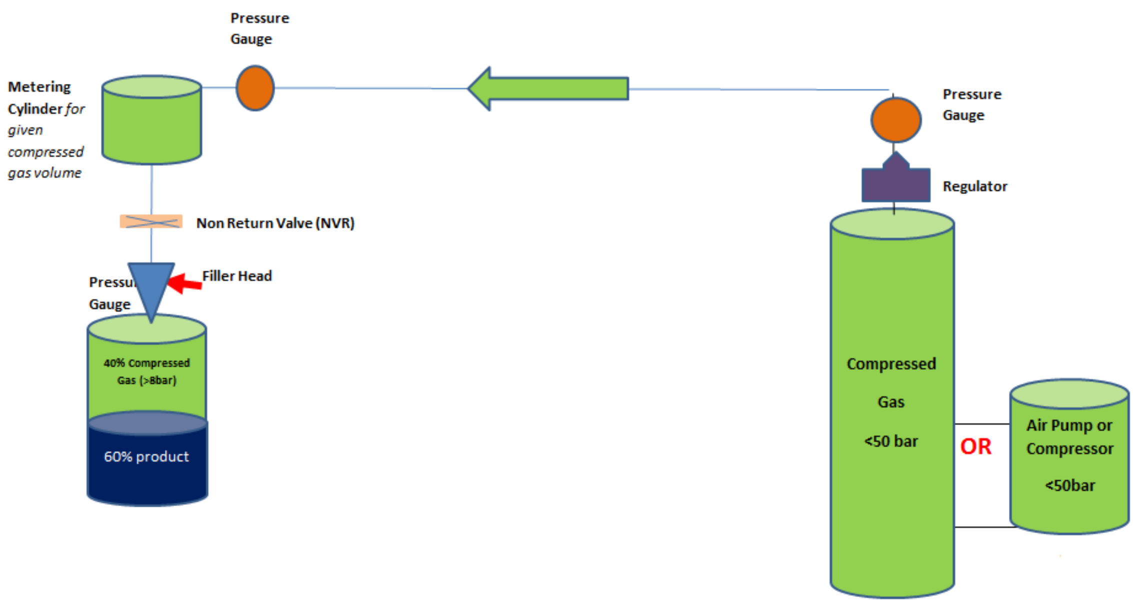


Figure 4.13: Impact Gassing

4.3.4. Pressure Gauge

The following Figure 4.14 shows the pressure gauge, which was also used in this investigation; the purpose of this device was to read the pressure of the can from the beginning to end of each pulsation. This gauge can was provided by COMES and it is able to measure the pressure up to 16 bar within ± 1 bar accuracy. The valve in hand contained a fitting that is placed onto the valve stem while the insert and actuator is removed.

Figure 4.14: Pressure Gauge

4.3.5. Electronic Weight Scale

The digital weight scale shown in Figure 4.15 was one of the measurement methods used, and it was used during each trial run. This was to ensure the correct measurement of the liquid discharge are by weighting the commercial cans or glass at timed intervals during spraying. When commercial or glass cans were used the difference of the glass can before and after each timed test sprayed showed the true discharge rate in g/s. This method has a margin of error in the account of fine drops being collected or vaporising. The scale used was provided from KERN equipment group and it worked with 230 VAC and 50/60 Hz and 10 Watts. This scale is capable of weighing a maximum weight of 4 kg within ±0.1 g accuracy.

Figure 4.15: Electronic Weight Scale

4.3.6. Laser Diffraction Machine

One of the methods commonly used to measure drop size distributions is laser diffraction supplied by Malvern. The laser drop-sizing measurement system is a non-intrusive system since sizing is done without forming particle image and it instantly samples a large number of droplets occupying a given volume [2]. This investigation utilised Mastersizer-X, and it measured the liquid and particles size droplets and it is the most used laser diffraction instrument. This method is known to be the most effective, reliable and simple one used to measure and characterise spray.

The measuring principle used is laser diffraction (Fraunhofer diffraction) which focuses on measuring the density of scattered light that is caused drops as it passed through the analyser sampling area [10]. A series of photo diodes found in the receiver unit is used to measure the density of scattered light. This laser diffraction consists of an optical bench, one end is known as the transmitter end and other is the receiver end. The transmitter end has a low power laser producing unit (He-Ne: 2 mW), and also a spatial filter; the combination of both produce a coherent and monochromatic beam of about 18 mm diameter, which is often known as analyser beam. The other end known as the receiver end is made of many lens, an obscuration monitor and a detector array; together with relevant hardware and computer interface [2]. Figure 4.16 shows the schematic optical arrangement seen in a laser diffraction instrument.

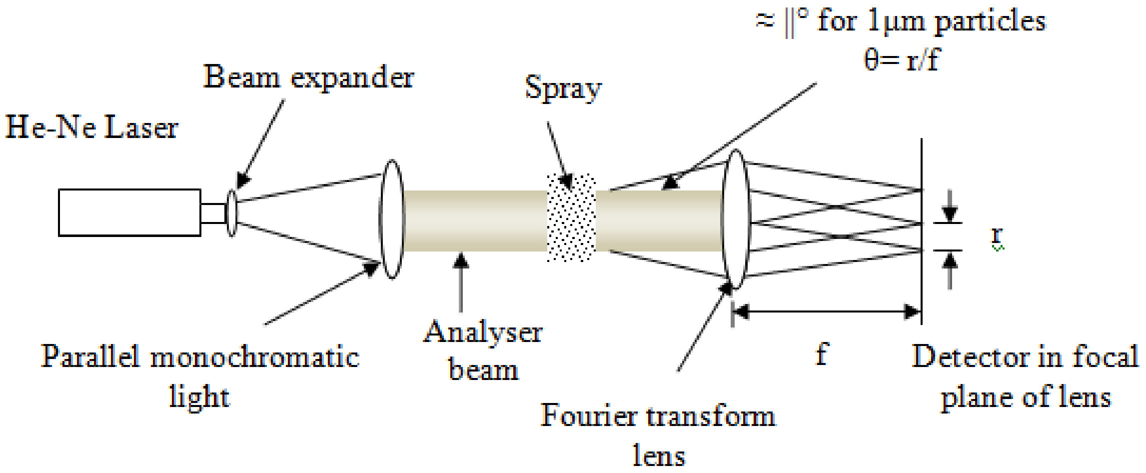


Figure 4.16: Optical arrangement employed in Laser Diffraction Analyser

4.3.7. Hand-Operating Clinching Machine

Figure 4.17 illustrates the clinching machine used in this investigation; its normal purpose is to attach assembled aerosol valve into the cans. The collets used in these machines tend to expand to push the metal of the valve cup found under the curl of the can.

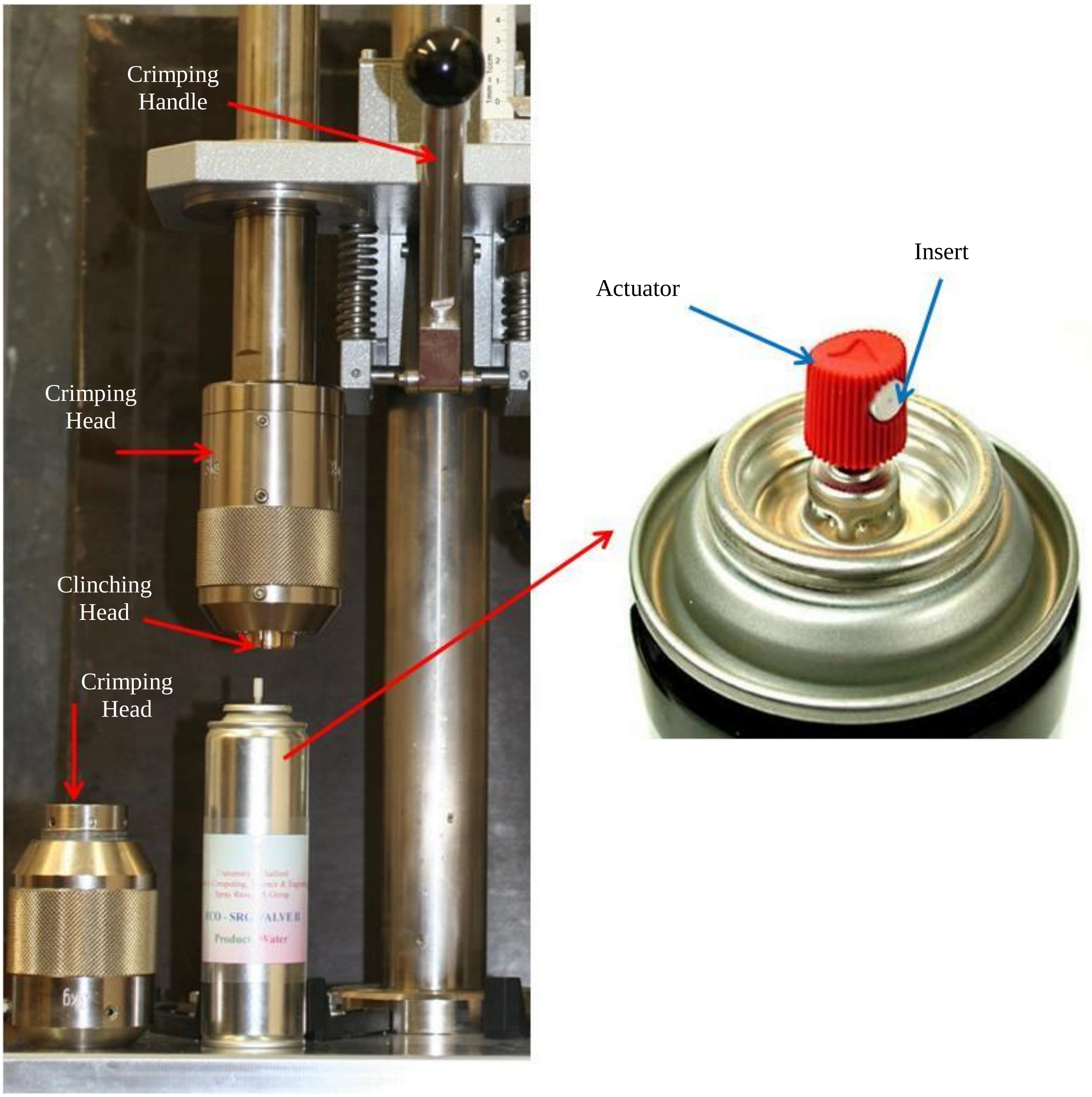


Figure 4.17: A Typical Hand Operated Clinching and Crimping Machine (Manufactured by DHL Ltd., UK)

4.4. Experimental Procedures and Data Acquisition

4.4.1. Continuous Spray

Table 4.2 shows the sample view of the data sheet in which all experimental data was inputted. From this table, the required data like the Discharge Rate of the liquid and the constancy of the flow can be extracted.

1. *Pressure (bar):* The initial pressure and also the pressure after each pulsation in the test.
2. *Weight (gr):* The initial weight and also the weight after each pulse.
3. *Time Interval (sec):* The duration of each actuation (i.e. 5 sec or 10 sec).

4. ΔW *(gr):* The difference on weight which was sprayed in each pulse is calculating automatically (difference between the weight before and after on each actuation).
5. *Discharge Rate (g/s):* The average discharge rate of the product which is sprayed in a second and it is calculated automatically by dividing the difference weight of the can before and after of the actuation over the time interval.
6. *% of the Sprayed Product:* The amount of liquid which was sprayed from the beginning of the test to the end.
7. *D(v,50):* The mean droplet size measurement which is measured by the laser diffraction analyser.

Table 4.2: Input Data Excel Sheet for Continuous Spray

	1	2	3	4	5	6	7
No.	Pressure (bar)	Weight (gr)	Time (sec)	ΔW (gr)	Discharge Rate (g/s)	% of Sprayed Products	Dv50
1	10	185.6					
2	8.5	180.5	10	5.1	0.51	5.1%	52.45
……							
10	3.8	85.1	10	3.8	0.38	100%	60.23

After filling the table, there are different graphs below the table, which are shown the Pressure, Flow Rate and Drop Sizes against the % of sprayed.

4.4.2. Metered Valve

Table 4.3 shows the sample view of the data sheet in which all experimental data was inputted. Description of the table:

1. *Start date and time:* The date and the time which the test has been started (i.e. 20/03/2016, 09:53).
2. *End date and time:* The date and the time which the test has been stopped and the measurement took place (i.e. 21/03/2016, 09:08).
3. *Duration (mins):* Duration between the start and end of the test in minutes (i.e. 1142mins).
4. *Number of Bursts:* The total number of bursts that happened in the above duration. This is automatically calculated by dividing the duration over the time interval which was set at the beginning (i.e. at 9 mins interval the number of total bursts is 1142 / 9 = 127).

5. *Total Number of Burst:* The total number of the bursts that the applied on the metered valve from beginning of the test till the end.
6. *Weight Before (gr):* The initial weight before starting the test.
7. *Weight After (gr):* The weight after the test stopped for measurement.
8. *Liquid Volume Sprayed (%):* The amount of liquid which was sprayed through the duration.
9. *Liquid Volume Sprayed (gr):* The difference on weight which was sprayed in run.
10. *Discharge Rate (µL/burst):* The liquid discharge flow rate.

Table 4.3: Input Data Excel Sheet for Metered Valve

1	2	3	4	5	6	7	8	9	10
Start	End	Duration (mins)	No. of Bursts (with 9mins Interval)	Total No. of Bursts	Weight Before (gr)	Weight After (gr)	% of Sprayed Products	ΔW (gr)	Discharge Rate (µL/Burst)
20/03/2016 09:53	21/03/2016 09:08	1142	127	127	462.1	446.0		16.1	127
21/03/2016 09:08									

After filling the table, the graph which shows the Discharge Rate against the Total Number of bursts will be presented.

4.5. Experimental Errors

The errors are random and would manifest themselves as scatter in data. When measurements are taking there are various sources of error that are systematic for a given set of data. The laser diffraction is capable of measuring drop size only in a certain range. The selection of receiver lens size depends upon the size range of particles to be measured. The source of errors within this type of instrument is multiple light scattering in which there is a possibility that the scattered light from one drop might be scattered again by other drops further down the beam axis, depending on the density of the spraying fluid. The laser diffraction instrument is equipped with an “obscuration level” indicator which can be used to determine if the spray is too dense or not; such a determination is often difficult. For example if the spray is positioned so that it does not project centrally across the laser beam of the laser instrument, there would be systematic errors as the can is evacuated with it remaining in the same position.

The liquid flow rate is measured during spraying using a stopwatch to spray for period of 3 s to 5 s, and weighting the glass can and its components before and after this period. The measured Liquid Flow rate is estimated to be accurate to within ±5%. There are indefinite transient effects because spraying start up and shut down when pressing and releasing the actuator to trigger the valve, cannot be truly immediate. The weight is measured to within ±0.1 g, a typical sprayed mass being 5-10 gr in 5 s.

The next Chapter will provide the results and discussions of the various combination designs which were tested during this investigation. The Chapter will present the results in relation to their performances (i.e. pressure drop, discharge flow rate and particle size). The complete results of “Excel Data Sheet” also provide in the relevant Appendix gives the detail analysis for each corresponding valve design.

CHAPTER 5

RESULTS AND DISCUSSION

5.1. Overview

This chapter presents with the results, analysis and discussion for both proposed investigation in Continuous Spray and Metered Valve.

Continuous Spray using inert gases (i.e. Nitrogen) as a propellant has been reported and published previously by Nourian et al [2]. However, the reduction of liquid discharge rate and thus the wetness which is the main aim of this investigation has been carried out and discussed in this Chapter.

Although the Metered Valve design has been fully piloted in production line and the report presented by Nourian et al [2], but this study has focused on modifying the design to perform better and acceptable by customer. The results which are presenting in this Chapter are related to the final modification on the Metered Valve design.

5.2. Continuous Spray Results

5.2.1. Wetness of Commercial Vs. SSG with Lower Discharge

In summary as can be seen in Figure 5.1 the level of wetness on the body, using conventional body spray with LPG propellant, can be comparable when EcoValve are used with compressed gas proving the discharge rates are reduced. This is discussed in the following Section (5.6.2).

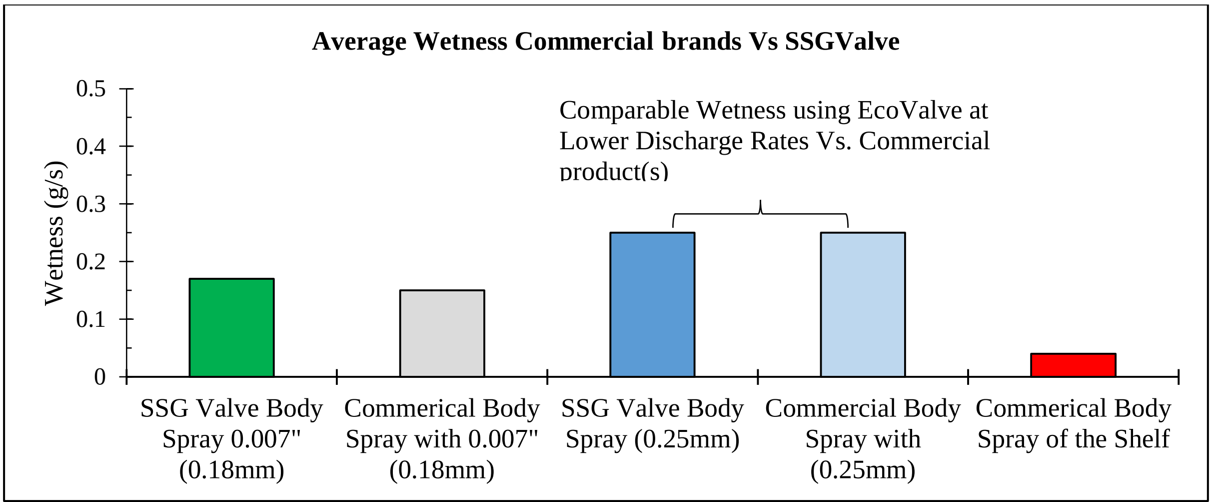


Figure 5.1: Average Wetness Commercial brand Vs. SSG Valve

5.2.2. Current Stem Design (Stem #0)

Figure 5.2 shows the results of spray performance for the current Continuous Spray aerosol valve design using water as a product filled with Nitrogen as a propellant. The results carried out using an actuator with 0.25 mm exit orifice insert and 60% fill ratio and 9 bar initial pressure.

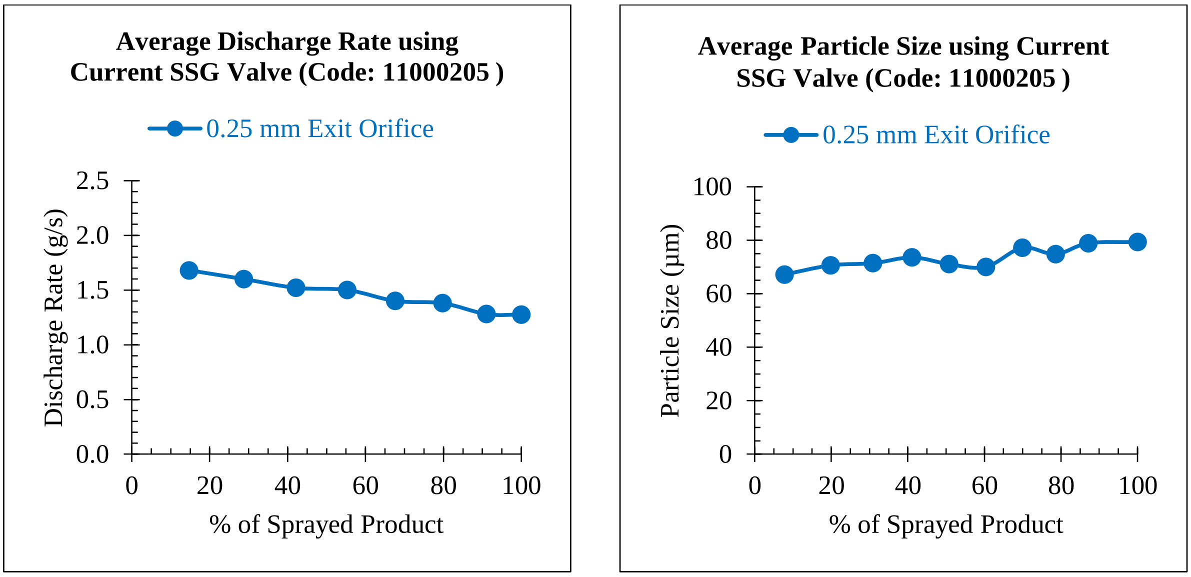


Figure 5.2: Spray Characterisation of the Current Stem Design (Stem #0)

As is shown above, the discharge flow rate decreased smoothly through the packlife of the can with constancy of 25% (from 1.7 g/s to 1.3 g/s) and the particle size increased from 67 µm to 80 µm with constancy of 20%. Figure 5.2 shows the spray images of beginning of the can and end of the can with the current stem design (Stem #0).


Beginning of the Can


End of the Can

Figure 5.3: Spray Images of the Current Stem Design (Stem #0)

5.2.3. Modifications on Stem Valve Design – Stem #1 and Stem #2

Figure 5.4 shows the comparison results of spray discharge rate for the current stem valve design (Stem #0) against the modified stems (Stem #1 and stem #2). The results conducted with using 60% fill ratio of water and 9 bar initial pressure with Nitrogen using 0.25 mm exit orifice insert.

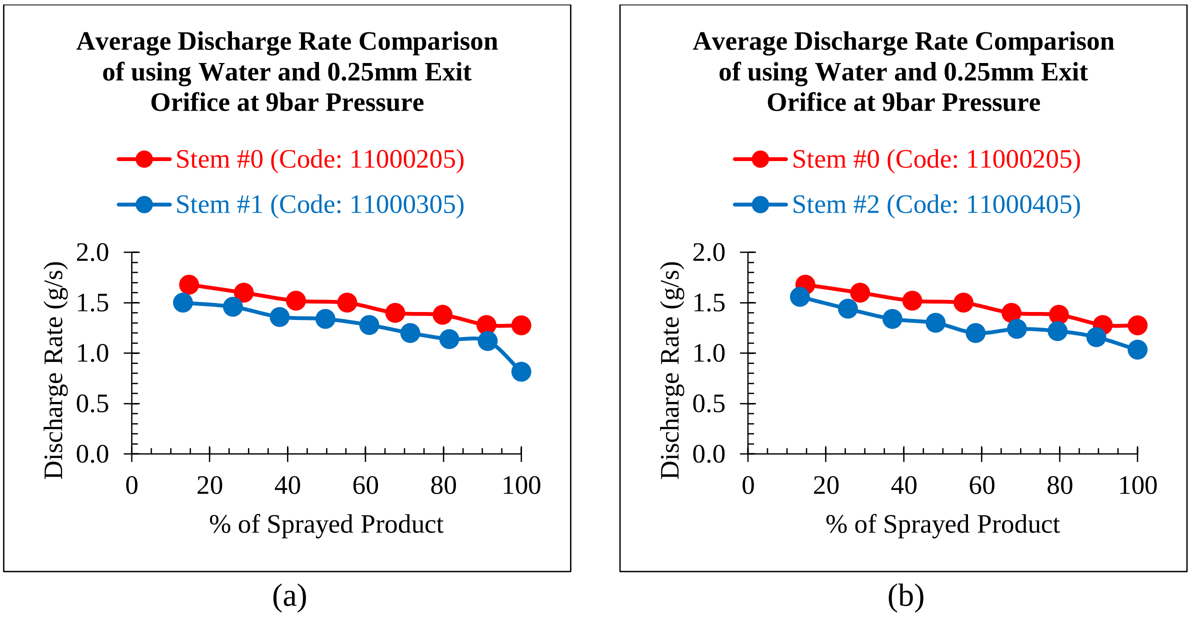
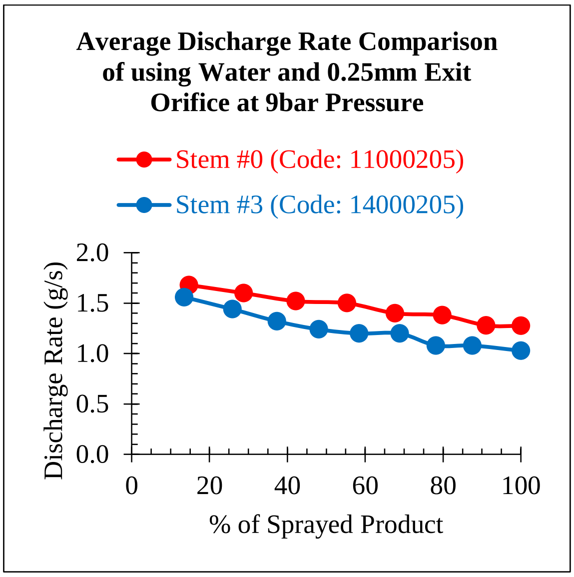


Figure 5.4: Discharge Rate Comparison between (a) Current Stem Design and Stem#1, (b) Current Stem Design and Stem #2

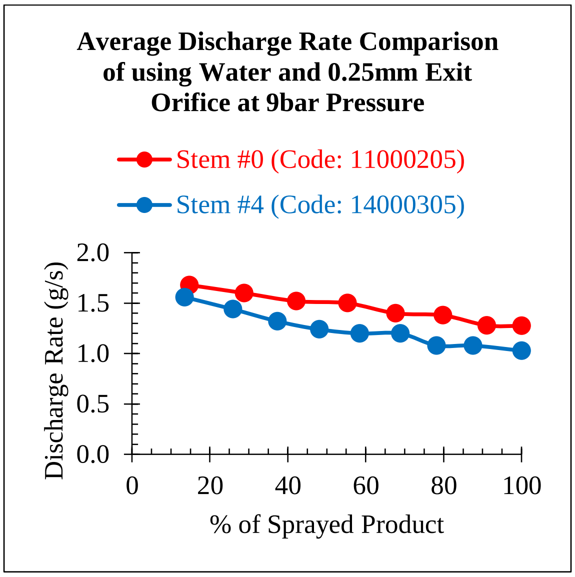
As is shown above, the discharge rate decreased about 12% on using Stem#1 (from 1.7 g/s on Stem#0 to 1.5 g/s) and the liquid discharge rate has a constancy of about 25% through the packlife of the can (from 1.5 g/s to 1.1 g/s). However, as the above results show, the discharge rate decreased about 6% using Stem#2 (from 1.7 g/s on Stem#0 to 1.6 g/s) and the constancy of the flow is about 38% from beginning to the end of the can (from 1.6 g/s to 1 g/s).

5.2.4. Modifications on Stem Valve Design – Stem #3, stem #4 and Stem #5

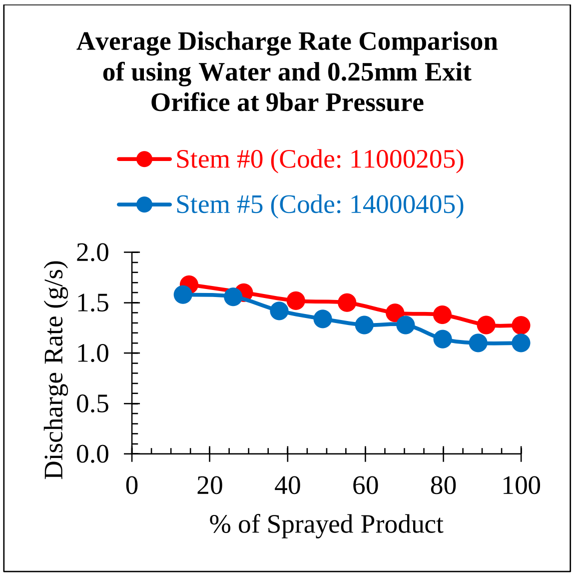
Figure 5.5 shows the comparison results of spray discharge rate for the current stem valve design (Stem #0) against the modified stems with enlarge mixing channel (Stem #3, Stem #4 and Stem #5). The results conducted with using 60% fill ratio of water and 9 bar initial pressure with Nitrogen using 0.25 mm exit orifice insert.



(a)



(b)



(c)

Figure 5.5: Discharge Rate Comparison between (a) Current Stem Design and Stem#3, (b) Current Stem Design and Stem #4 and (c) Current Stem Design and Stem #5

As is shown above, the discharge rate decreased about 6% on using Stem#3 and Stem #4 (from 1.7 g/s on Stem#0 to 1.4 g/s) and the liquid discharge rate has a constancy of about 37% through the packlife of the can (from 1.6 g/s to 1 g/s). However, as the above results show, the discharge rate using Stem #5 decreased about 2% with constancy of 30% from beginning to the end of the can (from 1.6 g/s to 1.1 g/s).

5.2.5. Modifications on Stem Valve Design – Stem #6, stem #7 and Stem #8

Figure 6.6 shows the comparison results of spray discharge rate for the current stem valve design (Stem #0) against the modified stems with reducing the half length of the mixing channel (Stem #6, Stem #7 and Stem #8). The results conducted with using 60% fill ratio of water and 9 bar initial pressure with Nitrogen using 0.25 mm exit orifice insert.

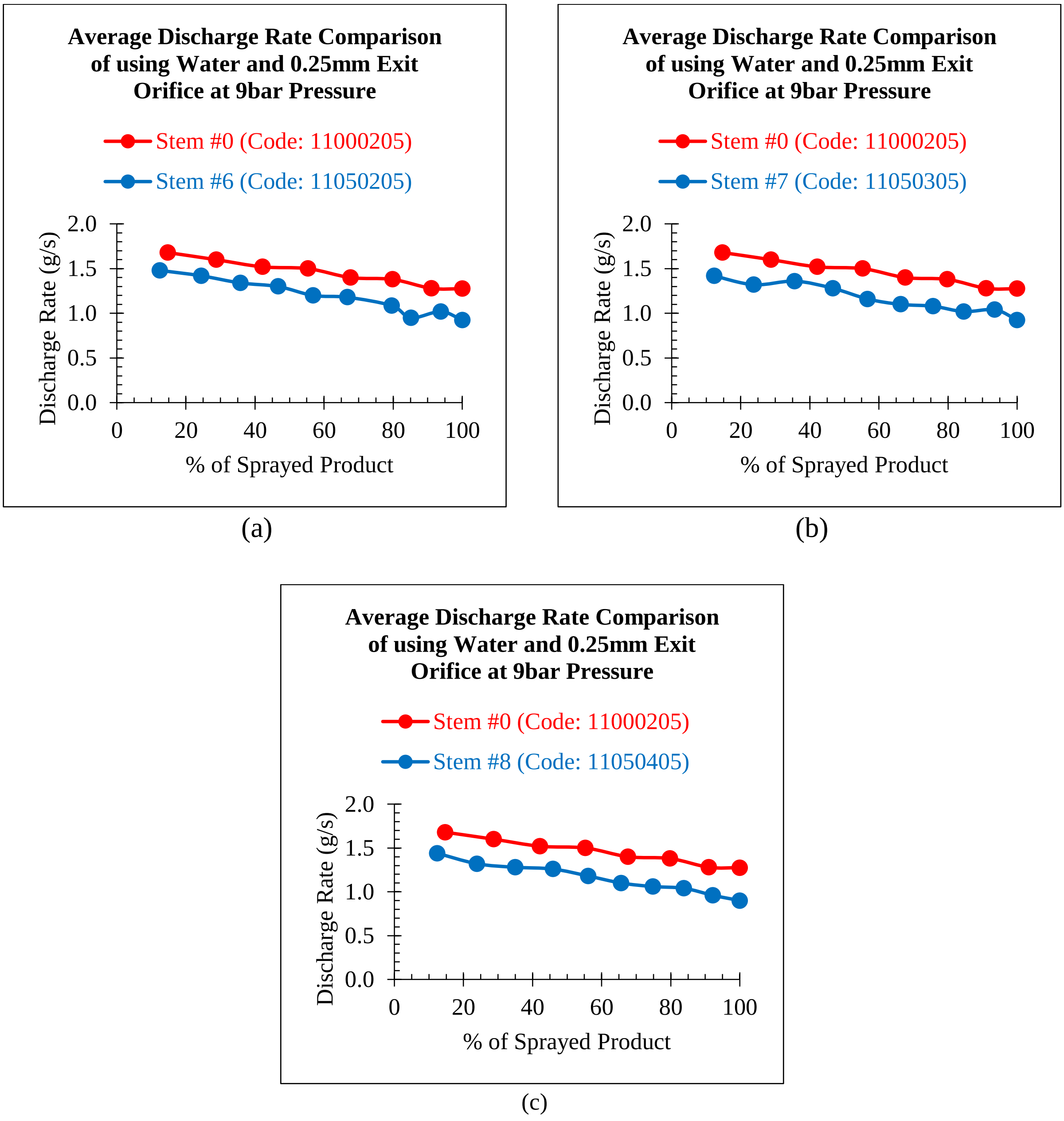


Figure 5.6: Discharge Rate Comparison between (a) Current Stem Design and Stem#6, (b) Current Stem Design and Stem #7 and (c) Current Stem Design and Stem #8

As is shown above, the discharge rate decreased about 18% on using all the above combination (Stem#6, Stem#7 and Stem#8) from 1.7 g/s on Stem#0 to 1.4 g/s. Also, the discharge rate constancy on all above combinations are about 28% from 1.4 g/s at beginning of the can to 1 g/s at the end of the can when the whole liquid has been evacuated.

Furthermore, Figure 5.7 shows the particle size comparison between the current stem design (Stem #0) and the modified stem (Stem #6) in which the particle sizes are almost similar. This is due to the reason that the laser diffraction machine is taking the spray sample from the centre core of the spray thus the particle sizes are similar.

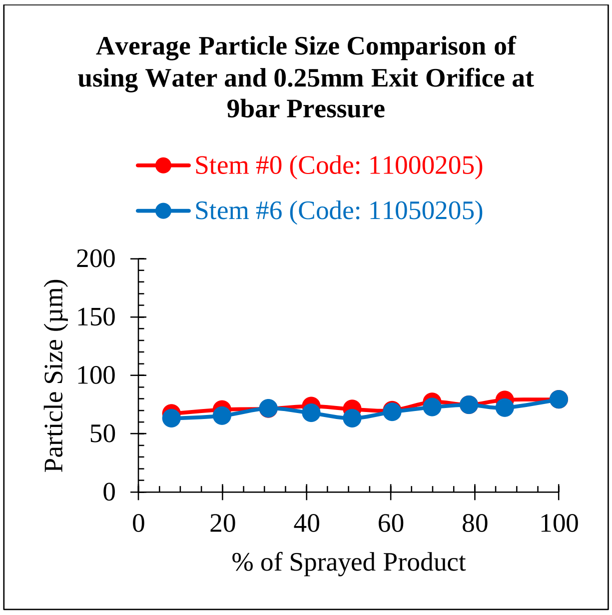
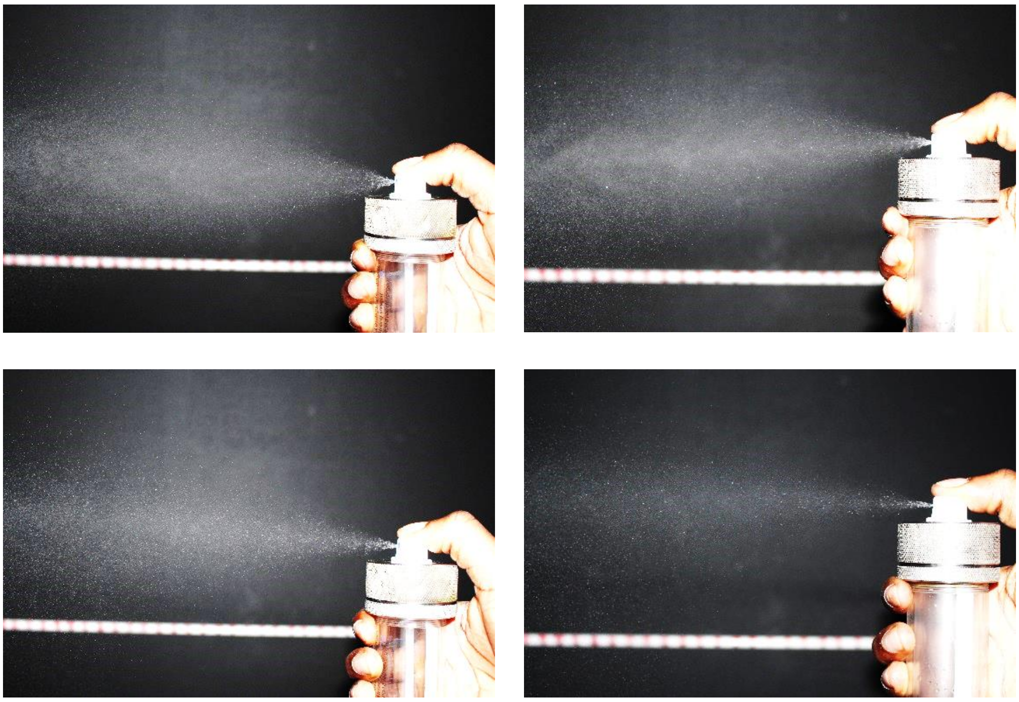


Figure 5.7: Particle Size Comparison between (a) Current Stem Design and Stem#6

Also as it shown below in Figure 5.8, the spray images of using modified stem (Stem #6) from beginning of the can to the End of the can is almost similar to the current stem design (Stem #0).

Beginning of the Can

End of the Can



Current Stem Design | Modified Stem #6

Figure 5.8: Comparison of Spray Images between Current Stem Design (Stem #0) and Modified Stem #6

5.2.6. Summary of the Results on Continuous Spray

Table 6.1 shows the summary of the results using continuous spray valve (current and modified stems).

Table 5.1: Results summary on Continuous Spray

Stem No.	Stem Code	Discharge Rate (g/s)	Constancy of Discharge Rate	Particle Size (µm)	Constancy of Particle Size
Stem #0	11000205	1.7 – 1.3	24%	67 – 79	18%
Stem #1	11000305	1.5 – 1.1	27%		
Stem #2	11000405	1.6 – 1.0	38%		
Stem #3	14000205	1.6 – 1.0	38%		
Stem #4	14000305	1.6 – 1.0	38%		
Stem #5	14000405	1.6 – 1.1	31%		
Stem #6	11050205	1.4 – 1.0	28%	63 – 79	25%
Stem #7	11050305	1.4 – 1.0	28%		
Stem #8	11050405	1.4 – 1.0	28%		

- As demonstrated above, the discharge rate can be reduced by 20% with using the modified stem #6 in which the discharge rate has the same constancy of 28% and the particle size is almost similar compared to the current stem design. This stem modification has been chosen for further analysis since the gas and liquid hole diameter are same as the current design and there is no need to change the pilot mould and the manufacturing cost will not be changed.

- In conclusion, the discharge rate of the spray was reduced from 1.4 g/s to less than 1.1 g/s (using the modified stem #6) throughout the life of the can thus providing lower wetness as also shown previously in Figure 5.1.

5.3. Metered Valve

The commercial Metered Valve products for airfreshners are based on an emulsion of perfume in water and it produces a fine spray and constant discharge rate on each actuation [2]. This is usually achieved by including a high proportion of liquefied propellant and using a vapour phase tap (VPT). The drop size of the commercial LPG metered valve is normally around 40 µm or less and the typical flow rate is less than 60 µL/Burst.

Figure 5.9 shows the spray characterisation (discharge rate and particle size) for the one of the commercial LPG metered valve from the market. As is shown below, the discharge rate is almost constant between 55 gr/burst and 60 gr/burst with the constant particle size of 30 µm.

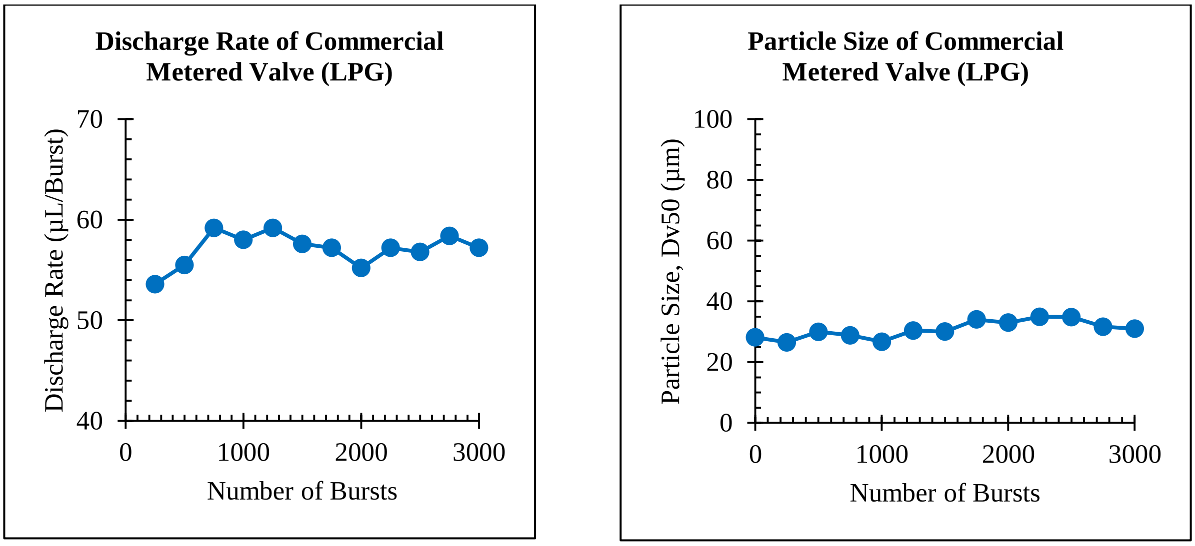


Figure 5.9: Spray Characterisation of the Commercial Metered Valve (LPG)

As explained previously in Chapter 4, the new metered valve design using compressed gas has been modified to produce the same performance compared to the LPG products. The design has been modified to produce the same liquid dosage as well as high dosage (for other applications). Figure 5.11 shows the spray discharge rate of a new metered valve design with short length of spigot to produce higher dosage (about 135 µL/burst). The test has carried out of using Water as a product with 60% fill ratio of the commercially available tinplate can (see Figure 5.10) and using the trigger box provided by one of the internationally recognised company (see Figure 5.10).

Figure 5.10: The Metered Valve Clinched onto the Can and Place onto the Trigger Box

As shown below, the Trigger box has been set on 9 minutes interval and the can performed constant through the packlife with 140 µL/burst on average and about totally 1600 bursts.

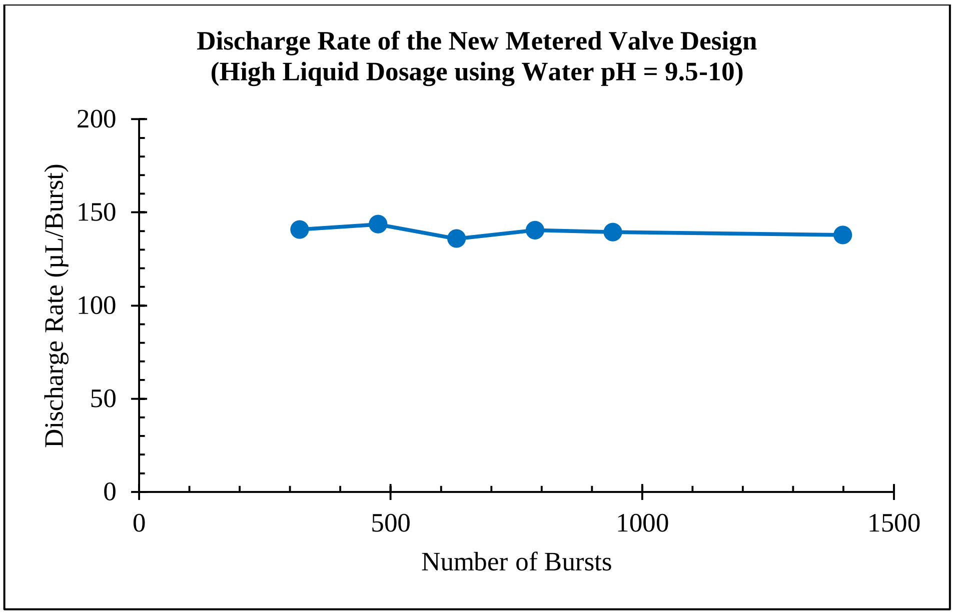


Figure 5.11: Spray Characterisation of the new Metered Valve Design with High Dosage Rate

The residue droplets do not change the discharge but could have led to oxidisation and electrical breakdown when placed in the Device. Hence the results obtained on the new valve design shows that avoid the residual droplet previously observed.

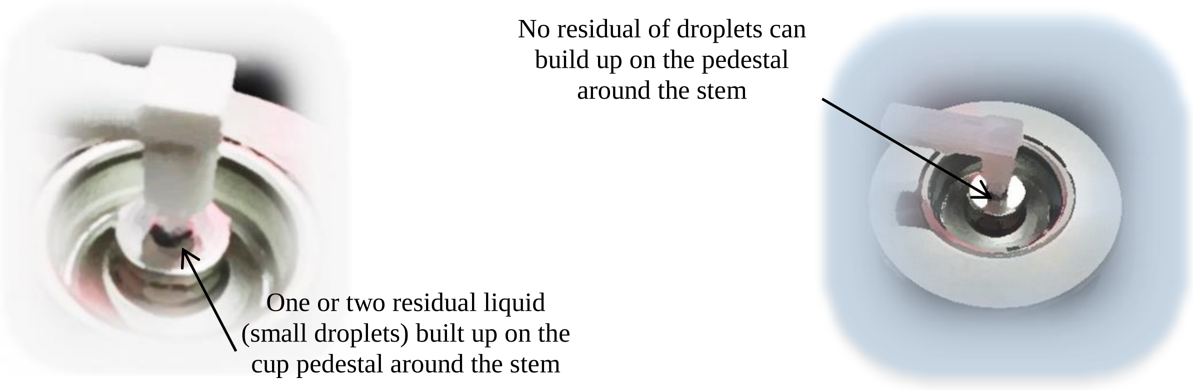


Figure 5.12: Comparison between Residual Liquids Built Up on the Cup Pedestal (Left) and (Right) No Residual Liquids Built Up on the Cup Pedestal

Figure 5.13 shows the comparison of spray images between the commercial LPG metered valve and the new metered valve design with high dosage as well as the spray patternation on both.

Commercial LPG Metered Valve

New Metered Valve with High Dosage Spray

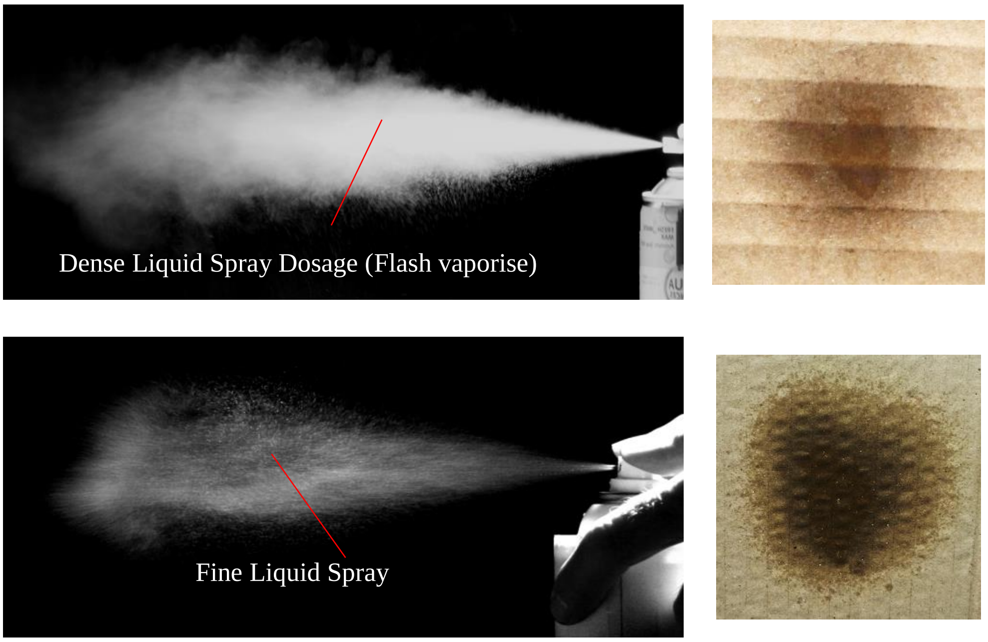


Figure 5.13: Comparison between Commercial LPG Metered Valve and New Metered Valve with High Dosage Spray (Left) Spray Images and (Right) Spray Patternation

As shown above, although the spray patternation of both valves are similar, but the commercial LPG metered valve produces a dense spray with flash vaporisation compared to the new metered valve design which has very fine spray utilising inert gas like Nitrogen.

Furthermore, Figure 5.14 demonstrates the spray performance of the new metered valve with low dosage of spray which is more compatible with the commercial airfreshener metered valve with LPG propellant.

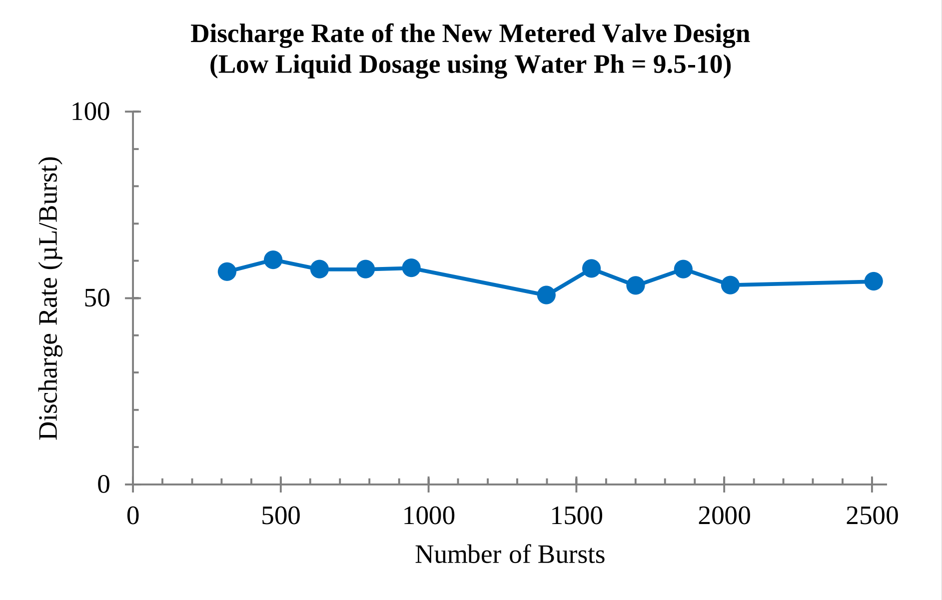


Figure 5.14: Spray Characterisation of the new Metered Valve Design with Low Dosage Rate

As shown above, the valve provides the spray discharge rate of 55 µL/burst over 2500 bursts from beginning to the end of the can.

5.3.1. Summary of the Results on Metered Valve

In summary the results are showing that the new metered valve design with High and Low dosage rate are performing well and acceptable compared to the current LPG products. The next step is to have more stability trials as well as commercial trials which the company is carrying out. Table 5.2 summarise all the above results.

Table 5.2: Results summary on Metered Valve

Product	Fill Ratio	Discharge Rate (µL/Burst)	Total No. of Burst	Penetration (mm)
Commercial *LPG*	70%	57 (average)	3000	500
New Metered Valve – *High Dosage*	60% Water	135 (average)	1400	500
New Metered Valve – *Low Dosage*	60% Water	55 (average)	2500	300

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusion

In this chapter the main conclusions obtained from this investigation are presented. As mentioned previously, this investigation has focused on two different aerosol products: (i) *Continues spraying* aerosol with matching valve_actuator using compressed gas propellant with reduction of wetness for boy spray products (ii) *Metered aerosol product* airfreshners, using a specially design compressed gas valve with 'L' shape actuator and MBU (Mechanical Breakup Unit) inserts, which are normally used as wall-mounted device.

6.1.1. Continuous Spray

In this investigation, in order to study a robust solution to reduce the flow discharge rate and the wetness using *Continues Spray* aerosol, the first step was to redesign the valve stem to give an overview on the base of this part of the investigation. Two designs were provided and tested in this investigation:

- The *first option* was to enlarge the valve stem mixing chamber from 1.1mm to 1.4mm. After testing the samples, it was concluded that the modification made on the mixing chamber it will create a disturbance on the flow discharge rate. It was found that this option is not ideal for reduction on the discharge rate, from the results it was shown that the average discharge rate for this design is about 1.35 g/s not much lower than the actual valve around 1.45 g/s.
    - This enables to reduce the flow discharge rate was about 7%.
- The *second option* was to reduce the valve stem mixing chamber from 1.1mm to 0.5 mm. After testing the samples, this option was found to reduce the flow discharge rate. The reduction on the mixing chamber gives a gradual improvement on the discharge rate. As is show on results the average discharge rate reduces from 1.45 g/s to 1.18 g/s through the packlife of the can by 20%. The results were comparable with commercial products using LPG and that showed comparable level of wetness using the product with compressed gas propellant.

6.1.2. Metered Spray

As a *second part* of this investigation, *Metered aerosol product* for airfreshners was redesigned and experimentally tested. This part of the investigation is divided into two phases:

- *Phase I* – redesigning a metered valve stem that prevents liquid droplet deposition around the stem. The following conclusions have been drawn:
  - By redesigning and relocating the stem liquid holes on the upper chamber (short stem stroke approximately 0.8 mm ± 0.1 mm) the problem with the residual of droplets that were built up on the pedestal around the stem were removed.
  - The modification also prevents the double actuation of liquid on each pulse
  - The discharge rates were between 100 µL to 120 µL as expected.
  - Less than 5% variation in volume per spray burst.
- *Phase II* – two new housing made of Nylon PA12 were designed with different spigot length:
  - Short Spigot (SS) that provided high liquid dosage (approximately 135 µL). A high dosage Metred valve tested with water which gives an average of 130 µL per burst with total of 1600 burst through the packlife.
  - Long Spigot (LS) that provided low liquid dosage (approximately 50 µL). Al ow liquid dosage Metered valve tested with water that give an average of 50 µL per burst with total of 2500 burst through the packlife.

In general, the data are quantitatively and qualitatively consistent as expected.

- All samples, tested worked through the packlife of the can with about 3 bar gas residue at the end of the can.
- The valves were tested using tinplate can with the automatic aerosol device (trigger box).
- Both valves types performed well with commercial ‘L’ shaped actuator and were tested with water (pH= 9.5 – 10.5) as product, with drop size (Dv_{50}) between 60 µm to 70 µm.
- Oven tests showed consistent stability of the pack.
- Less than 5% variation in volume per spray burst were found and provided good discharge rates with constancy of approximately 10% through the packlife.

- Two can types were used, US type with higher dome (can height= 120 mm) and EU type with lower dome (can height=18 mm).
- There is a normal tendency to the pedestal to rise when nitrogen is used as propellant.

6.2. Recommendations for Future work

The following are recommendations for future investigation:

- Further study should be made to investigate the combination of the modified valve stem using the new insert created to produce lower flow discharge rates.
- Application of CFD to the flow in the stem-insert system.
- Infrequent double upon the valve closure could be observed, although the spray still consistent with good discharge rate. Further study should be made into the automatic aerosol device due to the design of the trigger box which need to be with a swinging arm.
- The commercial actuator 'L' shape should be refined in order to obtain an enhance breakup with fine droplets, particularly on the low liquid dosage of 50 µL.

APPENDICES

Appendix A: Continuous Spray

- A-1 Current SSG Stem Design
- A-2 Modification on Stem Valve Design (Stem #1 and #2)
- A-3 Modification on Stem Valve Design (Stem #3, #4 and #5)
- A-4 Modification on Stem Valve Design (Stem #6, #7 and #8)

Appendix B: Metered Valve

Appendix A–1: Tabulated Results of Current SSG

Table 6.1: Current SSG Trial #1 and #2

Trial #1						
P (bar)	**W (gr)**	**ΔW (gr)**	**Time (sec)**	**Discharge Rate (g/s)**	**Particle Size (µm)**	**% Of Sprayed Products**
9.0	698.5					0
7.3	690.1	8.4	5	1.68	51.16	15
6.1	682.1	8.0	5	1.60	55.13	29
5.3	674.5	7.6	5	1.52	57.96	42
4.6	667.0	7.5	5	1.50	58.68	55
4.1	660.0	7.0	5	1.40	62.78	68
3.7	653.1	6.9	5	1.38	64.28	80
3.4	646.7	6.4	5	1.28	68.35	91
3.0	641.6	5.1	4	1.28	71.99	100

Trial #2						
P (bar)	**W (gr)**	**ΔW (gr)**	**Time (sec)**	**Discharge Rate (g/s)**	**Particle Size (µm)**	**% Of Sprayed Products**
9.0	698.5					0
7.2	690.3	8.2	5	1.64	58.03	14
6.2	682.3	8.0	5	1.60	61.84	28
5.1	674.8	7.5	5	1.50	61.36	42
4.5	667.3	7.5	5	1.50	62.62	55
4.0	660.2	7.1	5	1.42	72.18	67
3.6	653.2	7.0	5	1.40	71.62	80
3.3	646.7	6.5	5	1.30	75.91	91
3.0	641.5	5.2	4	1.30	80.68	100

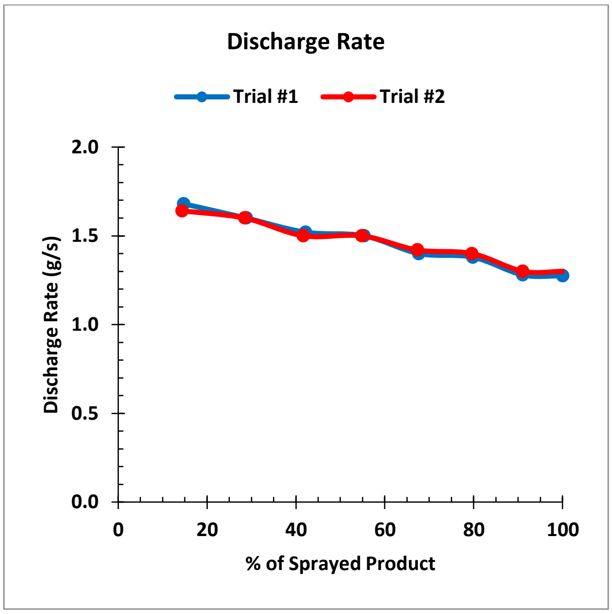


Figure 6.1: Spray Characterisation of the Current Stem Design (Stem #0), Trial #1 and #2

Appendix A–2: Tabulated Results of Modification on Stem Valve Design (Stem #1 and #2)

Table 6.2: Stem#1, Trial #1 and #2

Trial #1						
P (bar)	**W (gr)**	**ΔW (gr)**	**Time (sec)**	**Discharge Rate (g/s)**	**Particle Size (μm)**	**% Of Sprayed Products**
9.0	698.3					0
7.0	690.8	7.5	5	1.50	49.37	13
5.9	683.5	7.3	5	1.46	52.16	26
5.2	676.7	6.8	5	1.36	53.32	38
4.6	670.0	6.7	5	1.34	60.01	50
4.1	663.6	6.4	5	1.28	64.63	61
3.7	657.6	6.0	5	1.20	67.81	72
3.5	651.9	5.7	5	1.14	66.02	82
3.2	646.3	5.6	5	1.12	74.35	91
2.9	641.4	4.9	6	0.82	77.03	100

Trial #2						
P (bar)	**W (gr)**	**ΔW (gr)**	**Time (sec)**	**Discharge Rate (g/s)**	**Particle Size (μm)**	**% Of Sprayed Products**
9.2	698.5					0
7.0	691.0	7.6	5	1.53	50.34	14
5.6	683.5	7.3	5	1.48	53.05	29
4.8	677.3	6.9	5	1.37	60.01	36
4.1	671.0	6.7	5	1.34	64.63	52
3.7	663.4	6.3	5	1.32	66.98	61
3.4	656.8	6.0	5	1.20	69.00	75
3.1	652.0	5.8	5	1.13	69.49	83
2.8	646.6	5.6	5	1.11	74.66	94
2.6	644.9	4.9	6	0.79	71.21	100

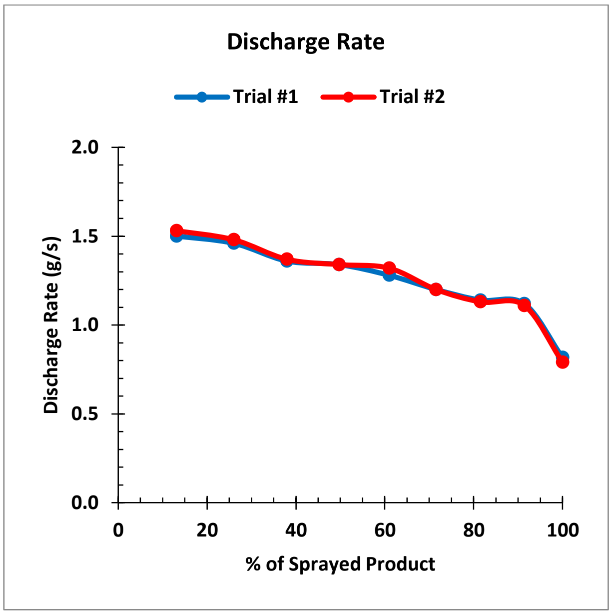


Figure 6.2: Discharge Rate Stem#1, Trial #1 and #2

Table 6.3: Stem#2, Trial #1 and #2

Trial #1						
P (bar)	**W (gr)**	**ΔW (gr)**	**Time (sec)**	**Discharge Rate (g/s)**	**Particle Size (µm)**	**% Of Sprayed Products**
9.4	699.8					0
7.4	692.0	7.8	5	1.56	51.73	13
6.2	684.8	7.2	5	1.44	54.19	26
5.4	678.1	6.7	5	1.34	57.12	37
4.8	671.6	6.5	5	1.30	60.62	48
4.4	665.6	6.0	5	1.20	63.98	58
3.9	659.4	6.2	5	1.24	66.98	69
3.6	653.3	6.1	5	1.22	68.77	79
3.3	647.5	5.8	5	1.16	70.67	89
2.9	641.3	6.2	6	1.03	73.02	100

Trial #2						
P (bar)	**W (gr)**	**ΔW (gr)**	**Time (sec)**	**Discharge Rate (g/s)**	**Particle Size (µm)**	**% Of Sprayed Products**
9.0	700.0					0
7.3	692.1	7.9	5	1.54	53.45	12
6.3	684.5	7.1	5	1.40	55.12	25
5.4	678.1	6.6	5	1.36	61.49	35
4.8	672.0	6.5	5	1.32	62.10	46
4.4	665.2	6.2	5	1.21	64.35	58
3.9	660.0	6.1	5	1.23	69.60	70
3.6	653.7	6.0	5	1.20	62.73	81
3.3	647.3	5.9	5	1.15	73.73	90
2.9	641.6	6.1	6	1.00	76.04	100

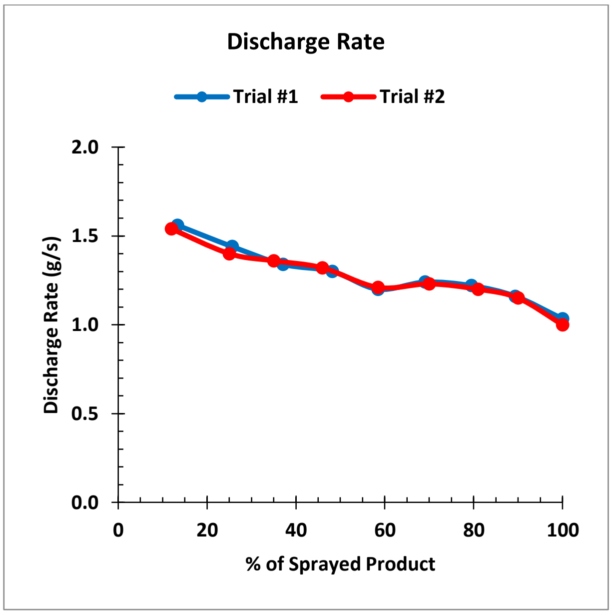


Figure 6.3: Discharge Rate Stem#2, Trial #1 and #2

Appendix A–3: Tabulated Results of Modification on Stem Valve Design (Stem #3, #4 and #5)

Table 6.4: Stem#3, Trial #1 and #2

Trial #1						
P (bar)	W (gr)	ΔW (gr)	Time (sec)	Discharge Rate (g/s)	Particle Size (µm)	% Of Sprayed Products
9.3	700.7					0
7.1	692.2	8.5	5	1.70	54.72	14
6.0	684.5	7.7	5	1.54	54.64	27
5.2	677.1	7.4	5	1.48	68.70	40
4.6	670.2	6.9	5	1.38	60.80	51
4.1	663.6	6.6	5	1.32	65.30	62
3.7	657.3	6.3	5	1.26	68.40	73
3.4	651.0	6.3	5	1.26	70.44	84
3.1	645.4	5.6	5	1.12	70.80	93
2.9	641.2	4.2	4	1.05	76.57	100

Trial #2						
P (bar)	W (gr)	ΔW (gr)	Time (sec)	Discharge Rate (g/s)	Particle Size (µm)	% Of Sprayed Products
9.0	700.0					0
7.2	692.3	8.3	5	1.73	49.29	16
6.1	683.5	7.7	5	1.53	53.43	25
5.0	677.0	7.3	5	1.48	55.81	41
4.4	670.2	7.0	5	1.40	63.11	53
4.0	663.8	6.8	5	1.31	68.42	61
3.7	658.3	6.5	5	1.25	73.81	75
3.3	651.6	6.3	5	1.26	67.40	82
3.2	644.4	5.5	5	1.11	74.94	91
3.0	640.0	4.1	3	1.03	77.73	100

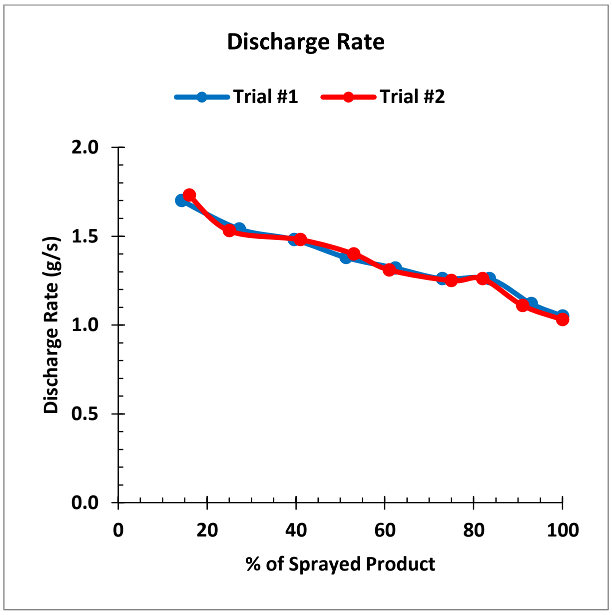


Figure 6.4: Discharge Rate Stem#3, Trial #1 and #2

Table 6.5: Stem#4, Trial #1 and #2

Trial #1						
P (bar)	W (gr)	ΔW (gr)	Time (sec)	Discharge Rate (g/s)	Particle Size (µm)	% Of Sprayed Products
9.1	699.0					0
7.2	691.2	7.8	5	1.56	51.26	13
6.1	684.0	7.2	5	1.44	54.00	26
5.4	677.4	6.6	5	1.32	59.98	37
4.8	671.2	6.2	5	1.24	63.47	48
4.4	665.2	6.0	5	1.20	64.71	58
3.9	659.2	6.0	5	1.20	67.05	69
3.6	653.8	5.4	5	1.08	72.86	78
3.4	648.4	5.4	5	1.08	73.54	88
3	641.2	7.2	7	1.03	77.54	100

Trial #2						
P (bar)	W (gr)	ΔW (gr)	Time (sec)	Discharge Rate (g/s)	Particle Size (µm)	% Of Sprayed Products
9.3	700.0					0
7.0	693.3	7.9	5	1.57	50.35	11
6.3	684.5	7.0	5	1.43	50.73	26
5.5	677.3	6.8	5	1.30	53.62	38
4.9	670.1	6.3	5	1.27	61.42	47
4.2	663.9	6.1	5	1.20	66.93	59
3.8	658.6	6.0	5	1.19	65.81	68
3.4	652.6	5.5	5	1.07	68.43	79
3.2	643.4	5.4	5	1.06	75.54	90
3.0	641.0	7.1	8	1.02	74.57	100

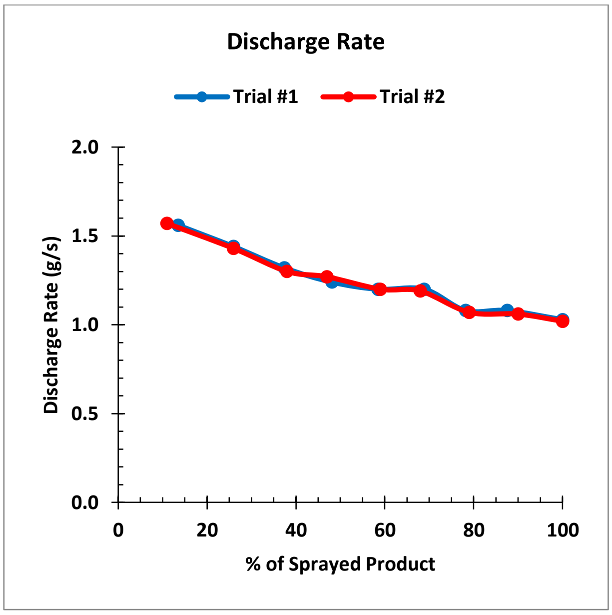


Figure 6.5: Discharge Rate Stem#4, Trial #1 and #2

Table 6.6: Stem#5, Trial #1 and #2

Trial #1						
P (bar)	**W (gr)**	**ΔW (gr)**	**Time (sec)**	**Discharge Rate (g/s)**	**Particle Size (μm)**	**% Of Sprayed Products**
9.2	701.5					0
7.1	693.6	7.9	5	1.58	53.15	13
5.9	685.8	7.8	5	1.56	54.68	26
5.1	678.7	7.1	5	1.42	54.34	38
4.5	672.0	6.7	5	1.34	60.05	49
4.0	665.6	6.4	5	1.28	65.45	60
3.6	659.2	6.4	5	1.28	67.85	70
3.4	653.5	5.7	5	1.14	70.65	80
3.1	648.0	5.5	5	1.10	75.30	89
2.6	641.4	6.6	6	1.10	77.23	100

Trial #2						
P (bar)	**W (gr)**	**ΔW (gr)**	**Time (sec)**	**Discharge Rate (g/s)**	**Particle Size (μm)**	**% Of Sprayed Products**
9.0	698.3					0
7.0	690.8	8.0	5	1.59	57.07	13
5.9	683.5	7.8	5	1.55	56.01	26
5.2	676.7	7.2	5	1.40	61.58	38
4.6	670.0	6.6	5	1.33	66.05	50
4.1	663.6	6.3	5	1.27	69.45	61
3.7	657.6	6.6	5	1.28	73.68	72
3.5	651.9	5.7	5	1.12	75.64	82
3.2	646.3	5.4	5	1.11	77.52	91
2.9	641.4	6.7	7	1.10	78.24	100

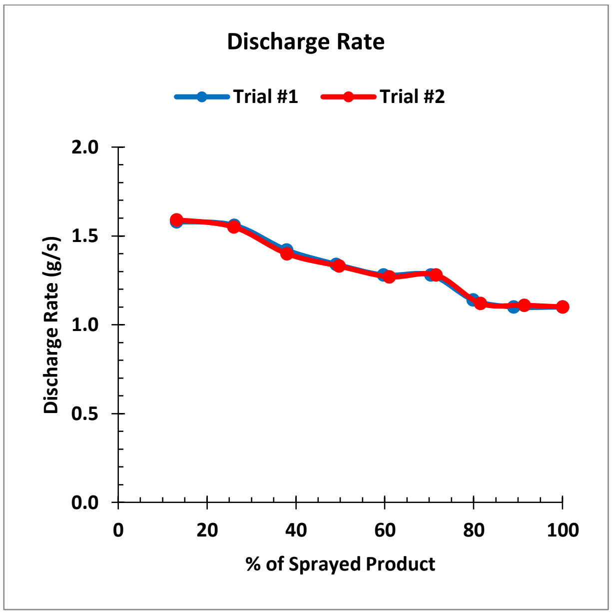


Figure 6.6: Discharge Rate Stem#5, Trial #1 and #2

Appendix A–4: Tabulated Results of Modification on Stem Valve Design (Stem #6, #7 and #8)

Table 6.7: Stem#6, Trial #1 and #2

Trial #1						
P (bar)	**W (gr)**	**ΔW (gr)**	**Time (sec)**	**Discharge Rate (g/s)**	**Particle Size (µm)**	**% Of Sprayed Products**
9.6	700.5					0
7.6	693.1	7.4	5	1.47	50.58	12
6.5	686.0	7.1	5	1.42	58.43	24
5.6	679.3	6.7	5	1.34	58.61	36
5.0	672.8	6.5	5	1.30	59.03	47
4.5	666.8	6.0	5	1.20	65.15	57
4.1	660.9	5.9	5	1.18	70.85	67
3.7	653.3	7.6	5	1.07	69.90	80
3.5	650.0	3.3	5	0.89	79.04	94
3.2	644.9	5.1	8	0.80	76.48	100

Trial #2						
P (bar)	**W (gr)**	**ΔW (gr)**	**Time (sec)**	**Discharge Rate (g/s)**	**Particle Size (µm)**	**% Of Sprayed Products**
9.6	699.8					0
7.6	692.0	7.3	5	1.46	51.63	11
6.5	684.8	7.0	5	1.40	58.46	22
5.6	678.1	6.6	5	1.33	59.59	34
5.0	671.6	6.6	5	1.27	70.57	46
4.5	665.6	6.1	5	1.20	69.00	58
4.1	659.4	6.0	5	1.18	76.48	66
3.7	653.3	7.4	5	1.10	76.50	80
3.5	647.5	3.5	5	0.92	78.65	85
3.2	641.3	5.0	8	0.83	77.23	100

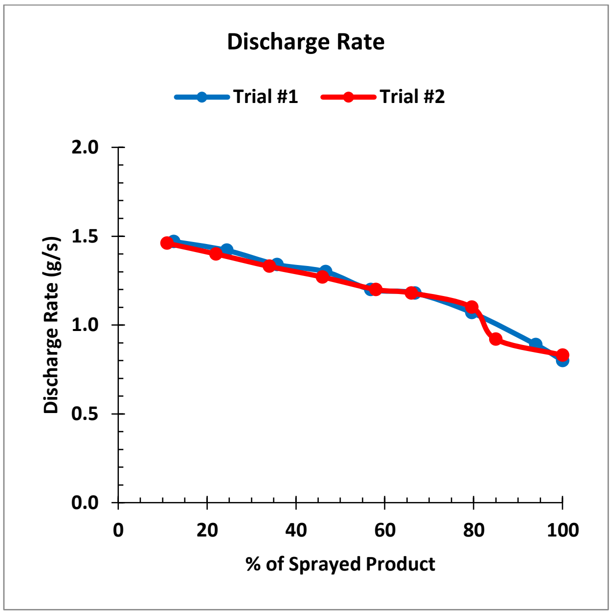


Figure 6.7: Discharge Rate Stem#6, Trial #1 and #2

Table 6.8: Stem#7, Trial #1 and #2

Trial #1						
P (bar)	**W (gr)**	**ΔW (gr)**	**Time (sec)**	**Discharge Rate (g/s)**	**Particle Size (µm)**	**% Of Sprayed Products**
8.9	708.8					0
7.2	701.7	7.1	5	1.42	48.28	12
6.2	695.1	6.6	5	1.32	47.18	24
5.5	688.3	6.8	5	1.36	50.08	36
4.9	681.9	6.4	5	1.28	55.97	47
4.4	676.1	5.8	5	1.16	57.61	57
4.1	670.6	5.5	5	1.10	57.27	66
3.8	665.2	5.4	5	1.08	59.70	76
3.5	660.1	5.1	5	1.02	62.30	85
3.3	654.9	5.2	4	1.04	63.69	100

Trial #2						
P (bar)	**W (gr)**	**ΔW (gr)**	**Time (sec)**	**Discharge Rate (g/s)**	**Particle Size (µm)**	**% Of Sprayed Products**
9.0	707.7					0
7.2	701.6	7.1	5	1.40	47.99	12
6.3	695.2	6.6	5	1.30	48.07	25
5.7	688.3	6.8	5	1.38	56.42	35
5.0	682.0	6.4	5	1.30	58.73	46
4.3	676.5	5.8	5	1.14	62.43	58
4.2	669.9	5.5	5	1.08	63.69	70
3.7	666.6	5.4	5	1.10	65.75	81
3.4	661.3	5.1	5	1.04	69.54	90
3.0	653.4	5.2	3	1.02	70.63	100

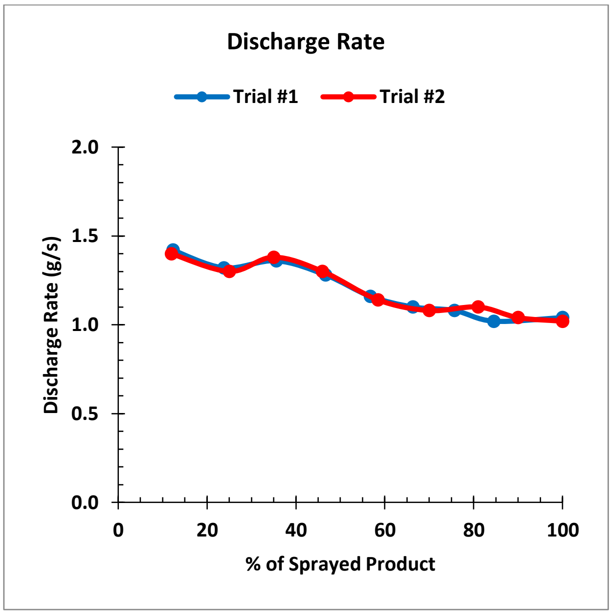


Figure 6.8: Discharge Rate Stem#7, Trial #1 and #2

Table 6.9: Stem#8, Trial #1 and #2

Trial #1						
P (bar)	**W (gr)**	**ΔW (gr)**	**Time (sec)**	**Discharge Rate (g/s)**	**Particle Size (µm)**	**% Of Sprayed Products**
9.6	708.9					0
7.2	701.7	7.2	5	1.44	53.24	12
6.3	695.1	6.6	5	1.32	54.59	24
5.5	688.7	6.4	5	1.28	57.77	35
5.0	682.4	6.3	5	1.26	66.56	46
4.5	676.5	5.9	5	1.18	69.72	56
4.1	671.0	5.5	5	1.10	70.83	66
3.8	665.7	5.3	5	1.06	73.18	75
3.5	660.5	5.2	5	1.04	74.91	84
3.3	655.7	4.8	5	0.96	75.30	100

Trial #2						
P (bar)	**W (gr)**	**ΔW (gr)**	**Time (sec)**	**Discharge Rate (g/s)**	**Particle Size (µm)**	**% Of Sprayed Products**
9.0	707.9					0
7.1	701.7	7.8	5	1.45	52.63	16
6.5	695.8	7.2	5	1.30	57.98	25
5.6	688.3	6.7	5	1.30	60.01	41
5.2	682.0	6.5	5	1.24	62.65	53
4.5	676.5	6.0	5	1.20	65.87	61
5.2	670.0	6.2	5	1.12	70.37	75
3.7	665.8	6.1	5	1.04	75.65	82
3.4	661.3	5.8	5	1.02	77.46	91
3.1	652.3	6.2	3	1.00	79.48	100

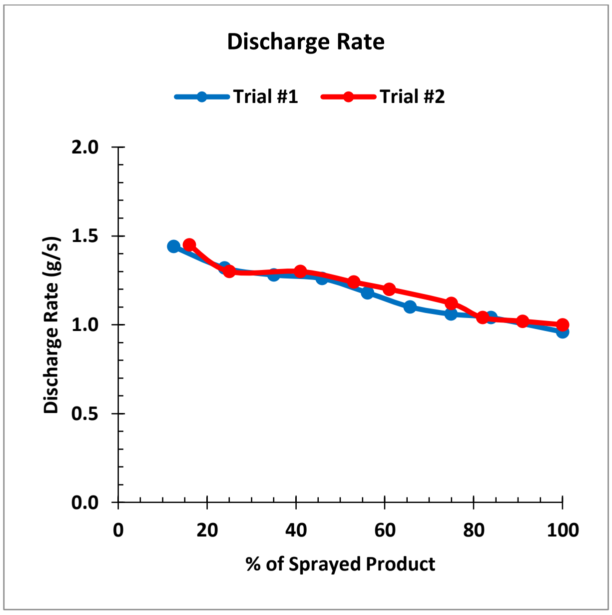
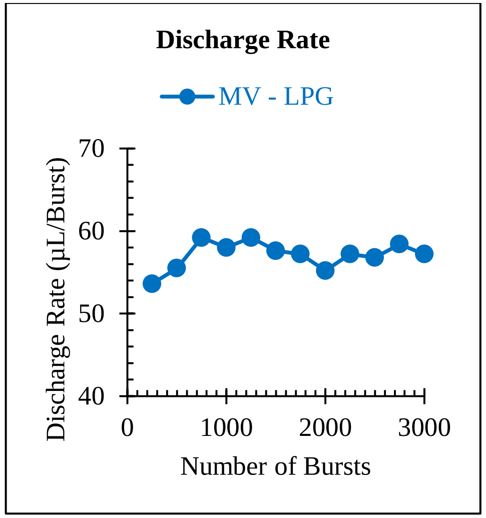


Figure 6.9: Discharge Rate Stem#8, Trial #1 and #2

Appendix B: Tabulated Results of Metered Valve

Table 6.10: Metered Valve LPG

Start	End	Duration (mins)	No. of Bursts (within 9 mins interval)	Total No. of Bursts	Weight Before (gr)	Weight After (gr)	ΔW (gr)	Discharge Rate (μL/Bursts)	Particle Size (μm)	% of Sprayed Products
3/21/16 9:00	3/22/16 22:30	2250	250	250	248.1	234.7	13.35	53.4	64.81	8
3/23/16 9:00	3/24/16 22:30	2250	250	500	234.7	220.8	13.90	55.6	65.26	16
3/28/16 9:00	3/29/16 22:30	2250	250	750	220.8	206.0	14.80	59.2	65.71	25
3/30/16 9:00	3/31/16 22:30	2250	250	1000	206.0	191.5	14.50	58.0	66.16	33
4/4/16 9:00	4/5/16 22:30	2250	250	1250	191.5	176.7	14.80	59.2	66.61	42
4/6/16 9:00	4/7/16 22:30	2250	250	1500	176.7	162.3	14.40	57.6	67.06	50
4/11/16 9:00	4/12/16 22:30	2250	250	1750	162.3	148.0	14.30	57.2	67.51	58
4/13/16 9:00	4/14/16 22:30	2250	250	2000	148.0	134.2	13.80	55.2	67.96	66
4/18/16 9:00	4/19/16 22:30	2250	250	2250	134.2	119.9	14.30	57.2	68.41	75
4/20/16 9:00	4/21/16 22:30	2250	250	2500	119.9	105.7	14.20	56.8	68.86	83
4/25/16 9:00	4/26/16 22:30	2250	250	2750	105.7	91.1	14.60	58.4	69.31	92
4/27/16 9:00	4/28/16 22:30	2250	250	3000	91.1	76.8	14.30	57.2	69.76	100



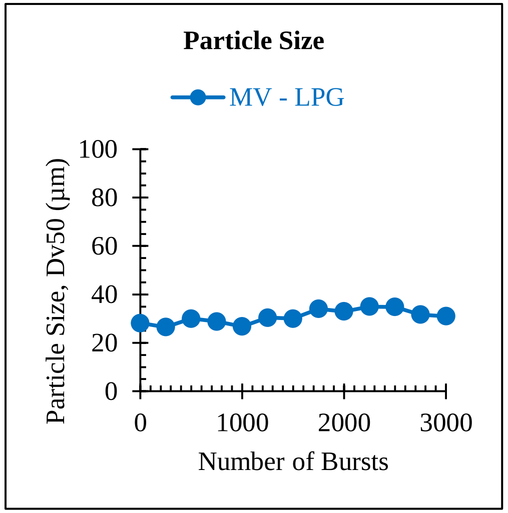


Figure 6.10: Spray Characterisation of the Commercial Metered Valve (LPG)

Table 6.11: Modified Metered Valve (High liquid Dosage)

Start	End	Duration (mins)	No. of Bursts (within 9 mins interval)	Total No. of Bursts	Weight Before (gr)	Weight After (gr)	ΔW (gr)	Discharge Rate (µL/Bursts)	Particle Size (µm)	% of Sprayed Products
7/9/2016 12:35	7/11/2016 12:30	2875	250	319	507	462.1	44.9	141	64.81	22.45
7/11/2016 13:00	7/12/2016 12:30	1410	250	475	462.1	439.7	22.4	144	65.26	33.65
7/12/2016 13:00	7/13/2016 12:30	1410	250	631	439.7	418.5	21.2	136	65.71	44.25
7/13/2016 13:00	7/14/2016 12:30	1410	250	787	418.5	396.6	21.9	140	66.16	55.2
7/14/2016 13:13	7/15/2016 12:30	1397	250	942	396.6	375	21.6	139	66.61	66
7/15/2016 13:00	7/18/2016 9:41	4121	250	1399	375	312	63	138	67.06	97.5

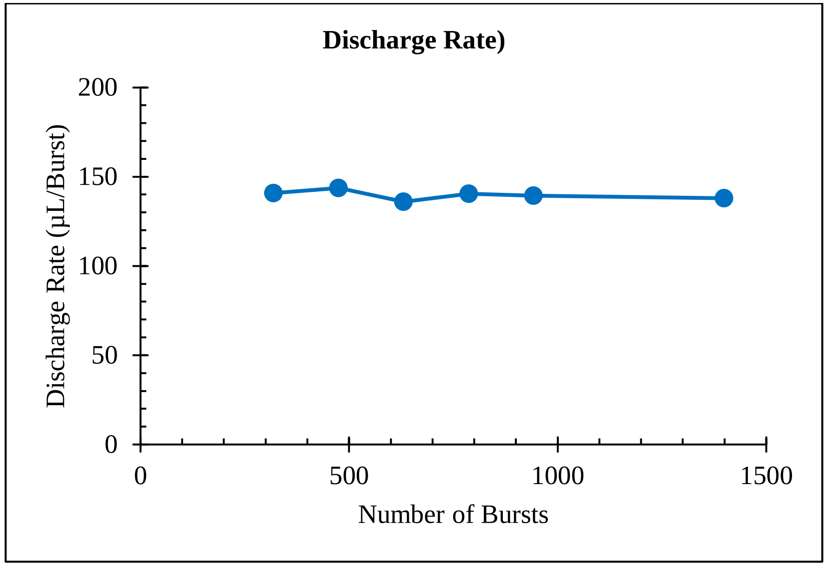


Figure 6.11: Spray Characterisation of the new Metered Valve Design with High Dosage Rate

Table 6.12: Modified Metered Valve (Low liquid Dosage)

Start	End	Duration (mins)	No. of Bursts (within 9 mins interval)	Total No. of Bursts	Weight Before (gr)	Weight After (gr)	ΔW (gr)	Discharge Rate (μL/Bursts)	Particle Size (μm)	% of Sprayed Products
7/9/2016 12:35	7/11/2016 12:30	2875	319	319	506.6	488.4	18.2	57	64.81	9.3
7/11/2016 13:00	7/12/2016 12:30	1410	156	475	488.4	479	9.4	60	65.26	14
7/12/2016 13:00	7/13/2016 12:30	1410	156	631	479	470	9	58	65.71	18.5
7/13/2016 13:00	7/14/2016 12:30	1410	156	787	470	461	9	58	66.16	23
7/14/2016 13:13	7/15/2016 12:30	1397	155	942	461	452	9	58	66.61	27.5
7/15/2016 13:00	7/18/2016 9:41	4121	457	1399	452	428.8	23.2	51	67.06	39.1
7/18/2016 10:20	7/19/2016 9:14	1374	152	1551	428.8	420	8.8	58		43.5
7/19/2016 11:19	7/20/2016 9:50	1351	150	1701	420	412	8	53		47.5
7/20/2016 10:08	7/21/2016 10:19	1451	161	1862	412	402.7	9.3	58		52.15
7/21/2016 10:31	7/22/2016 10:25	1434	159	2021	402.7	394.2	8.5	53		56.4
7/22/2016 13:34	7/25/2016 14:23	4369	485	2506	394.2	367.8	26.4	54		69.6

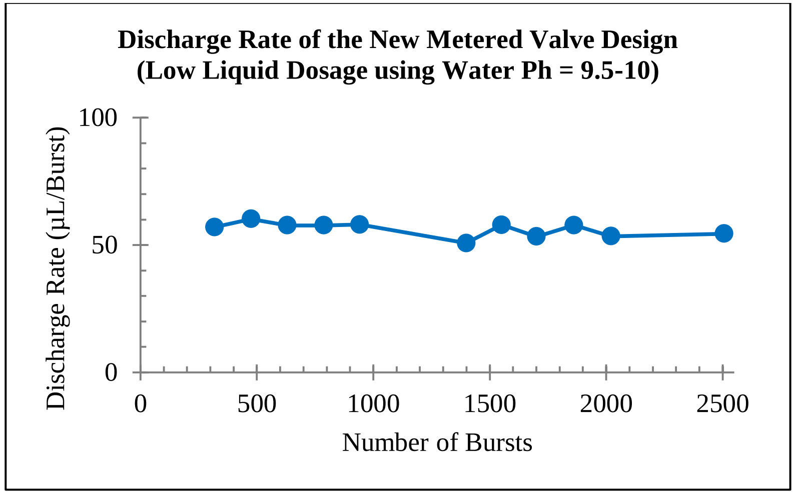


Figure 6.12: Spray Characterisation of the new Metered Valve Design with High Dosage Rate

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